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TRADE-OFF BETWEEN LAND VEHICLE ANTENNA COST AND GAIN FOR SATELLITE MOBILE COMMUNICATIONS

INTERIM REPORT

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TABLE OF CONTENTS

Section			Page
1.0	SUMMARY		1-1
2.0	INTRODUCTION		2-1
3.0	STUDY OBJECTIVES		3-1
	3.1	Cost Estimate Requirements	3-5
	3.2	Design Changes	3-7
4.0	CANDIDATE ARRAY ELEMENTS		4-1
	4.1	Dipole Type Antennas	4-3
	4.2	Spiral Antenna Types	4-9
	4.3	Slot Antennas	4-13
	4.4	Aperture Antennas	4-21
	4.5	Conformal Antenna	4-21
5.0	POTENTIAL ARRAYING TECHNIQUES		5-1
	5.1	Colinear Array	5-1
	5.2	Linear Array	5-1
	5.3	Planar Array	5-1
	5.4	Ring Array	5-1
	5.5	Surface Wave	5-3
6.0	SCANNING TECHNIQUES		6-1
	6.1	Elevation Scanning	6-1
	6.2	Azimuth Scanning	6-1
7.0	TRACKING METHODS		7-1
	7.1	Magnetic Compass	7-1
	7.2	Pseudo Sequential Lobing	7-1
	7.3	AGC Tracking	7-7
8.0	NINE ANTENNAS SELECTED FOR COSTING		8-1
	8.1	Linear Array	8-1
	8.2	Helix Array	8-1
	8.3	Parabolic Antenna	8-10
	8.4	Horn Antenna	8-10
	8.5	Patch Array	8-10
	8.6	Corner Reflector	8-19
	8.7	Monopole Array	8-19
	8.8	Ring Array	8-19
	8.9	Conformal Array	8-19

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TABLE OF CONTENTS

Section			Page
9.0	TWO SATELLITE ISOLATION STUDY		9-1
	9.1	Introduction	9-1
	9.2	Look Angle Calculation	9-1
	9.3	Isolation Model	9-6
	9.4	Isolation Calculation	9-8
		9.4.1 Reflector Antenna	9-8
		9.4.2 Linear Array Antenna	9-15
		9.4.3 Planar Array	9-22
		9.4.4 Ring Array	9-31
		9.4.5 Isolation Enhancement Techniques	9-31
		9.4.6 Conclusions	9-36
10.0	ANTENNAS SELECTED FOR FURTHER STUDY		10-1
	10.1	Ring Array	10-1
	10.2	2 x 5 Patch Array	10-7
11.0	COST RATIONALE		11-1
12.0	BREADBOARD AND PROTOTYPE DEVELOPMENT		12-1
APPENDIX A:	Learning Curve Analysis for Production Quotes		
APPENDIX B:	Detailed Cost Data		

LIST OF ILLUSTRATIONS

Figure No.	Title	Page
1-1	Cost for 100 Units	1-2
1-2	Cost for 10,000 Units	1-3
3-1	Example of Cost-versus-Gain for Various Mobile Antenna Designs	3-6
4-1	Dipole in Corner Reflector	4-4
4.1-1	Picture of Shortened Dipole	4-5
4.1-2	Patterns of Asymmetrical Dipole	4-6
4.1-3	Crossed "V" Dipole Antenna	4-7
4.1-4	Crossed "V" Dipole Radiation Pattern Optimum Ground Plane Spacing	4-8
4.1-5	Picture of Grating and Corner Reflector and Grating	4-10
4.1-6	Polarization Grating and Corner Reflector	4-11
4.1-7	Corner Reflector and Grating	4-12
4.2-1	Six Turn Helix Tilted 30 Degrees	4-14
4.2-2	Six Turn Helix Tilted 20 Degrees	4-15
4.2-3	Six Turn Helix Tilted 20 Degrees	4-16
4.2-4	Six Turn Helix Parallel to Ground Plane	4-17
4.2-5	Eight Turn Helix	4-18
4.3-1	Slot Dipole Radiator	4-19
4.3-2	Slot Dipole Elevation Pattern	4-20
4.5-1	Cross Slot Antenna	4-22
7.1-1	Magnetic North Seekers Servo System	7-2
7.1-2	Compass Data	7-3
7.1-3	Geomagnetic Declination Contours	7-4
7.2-1	Pseudo Sequential Lobing System Block Diagram	7-5

LIST OF ILLUSTRATIONS (Continued)

Figure No.	Title	Page
7.2-2	Development of Sequentially Lobed Beam	7-6
7.2-3	Switching Through Rotary Joint	7-8
7.2-4	Motor Drive	7-9
7.2-5	Servo System Block Diagram	7-10
8-1	Linear Array Antenna (12 dBcp Gain)	8-2
8.1-1	Circuit Board and Assembly	8-3
8.1-2	Crossed Slot Elevation Pattern	8-4
8.2-1	Helical Antenna	8-7
8.3-	Parabolic Antenna	8-11
8.4-1	Gain Horn Antenna - 9 dBcp Gain	8-14
8.4-2	Gain Horn Antenna - 12 dBcp Gain	8-15
8.4-3	Lobe Switching and Beam Switching	8-16
8.5-1	Patch Antenna	8-17
8.5-2	Radiation Pattern of Patch with Rotating Linear	8-18
8.7-1	Monopole Two Element Array	8-20
8.9-1	Gain Conformal Antenna 9 dBcp	8-22
9-1	Geocentric Frame of Reference	9-2
9-2	Satellite Coordinates	9-5
9-3	Selected Satellite Coordinates	9-7
9-4	Corner Reflector Elevation Pattern	9-10
9-5	Corner Reflector Azimuth Pattern	9-11
9-6	Corner Reflector	9-12
9-7	12-inch x 14-inch Reflector with Cosine Illumination	9-14
9-8	Array Factor Computation	9-16

LIST OF ILLUSTRATIONS (Continued)

Figure No.	Title	Page
9-9	Helix and Horn Pattern Computation	9-17
9-10	1 x 2 Helix Array	9-19
9-11	1 x 4 Helix Array	9-20
9-12	2 x 5 Crossed Slot Array	9-21
9-13	1 x 4 Horn Array	9-23
9-14	2 x 4 Horn Array	9-24
9-15	Rectangular Planar Array	9-25
9-16	Six-Element Array Factor Computation	9-29
9-17	Triangular Planar Array	9-32
10-1	Ring Array	10-2
10-2	Antenna Schematic	10-3
10-3	Commutator Equivalent Circuit	10-4
10-4	Commutator VSWR	10-5
10-5	Commutator	10-6
10-6	Ground Plane Effects on Edge Mounted Antenna	10-9
10.2-1	Patch Array	10-10
11-1	Cost for 100 Units	11-2
11-2	Cost for 10,000 its	11-3

LIST OF TABLES

Table No.	Title	Page
1-1	Performance Summary Table	1-4
4-1	Potential Array Elements	4-2
5-1	Potential Array Configurations	5-2
6-1	Potential Scanning Techniques	6-2
8.1-1	Minimum Gain over Coverage Area	8-5
8.1-2	Antenna Pattern Performance	8-6
8.2-1	Helix Gain Characteristics	8-8
8.2-2	Radiation Pattern Characteristics	8-9
8.3-1	Parabolic Antenna Gain	8-12
8.3-2	Parabolic Antenna Radiation Pattern Characteristics	8-13
8.7-1	Monopulse Array Performance Characteristics	8-21
8.9-1	Conformal Array Gain	8-23
9-1	Satellite Coordinates	9-5
9-2	Reflector Type Antennas	9-9
9-3	Linear Arrays	9-18
9-4	Horn 3-dB Beamwidths	9-22
9-5	Planar Array Phase Shift Data	9-27
9-6	Planar Array Isolation	9-30
9-7	Illumination Tailoring	9-33
9-8	Shielding	9-34
9-9	Polarization Diversity	9-35
9-10	Isolation Comparison	9-37
10-1	Ring Array Gain Analysis	10-8
10.2-1	Patch Antenna Array Performance	10-12

LIST OF TABLES (Continued)

Table No.	Title	Page
11-1	One Unit Cost of Major Antenna Subassemblies	11-4
12-1	Breadboard Cost and Schedule	12-1
12-2	Prototype Cost and Schedule	12-1

1.0 SUMMARY

The cost-performance feasibility of nine antenna types was established for the M-SAT(X) Mobile Antenna. The range in cost is shown in Figures 1-1 and 1-2 for wholesale costs in 1983 dollars without profit. The range in performance is shown in Table 1-1. As can be seen the price range is acceptable for a large volume market for most of the antennas studied. The technical performance of most antennas studied meets the requirements except for radiation pattern fall-off near the horizon. However, for minimum height the linear array and the ring array would be the antennas of choice, all things considered. The conformal array does have minimum height but is very expensive. Some portions of the study require further work in order to demonstrate the feasibility of the concept in a practical light. Such a study should focus on the blocking of the 2x5 linear array elements. Methods of implementing the commutator and phase shifters need experimental work to demonstrate feasibility of the ring array.

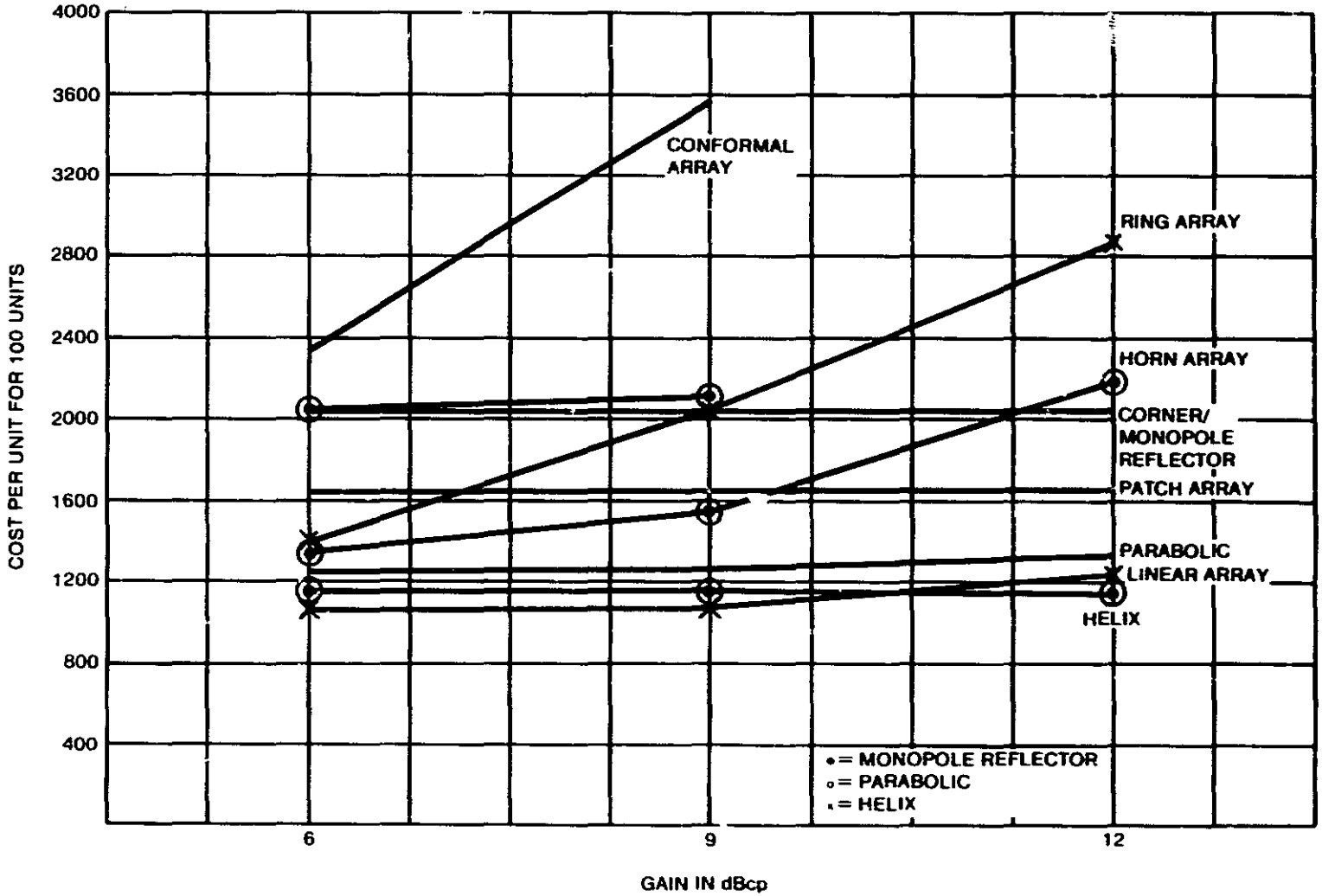


FIGURE 1-1. COST FOR 100 UNITS

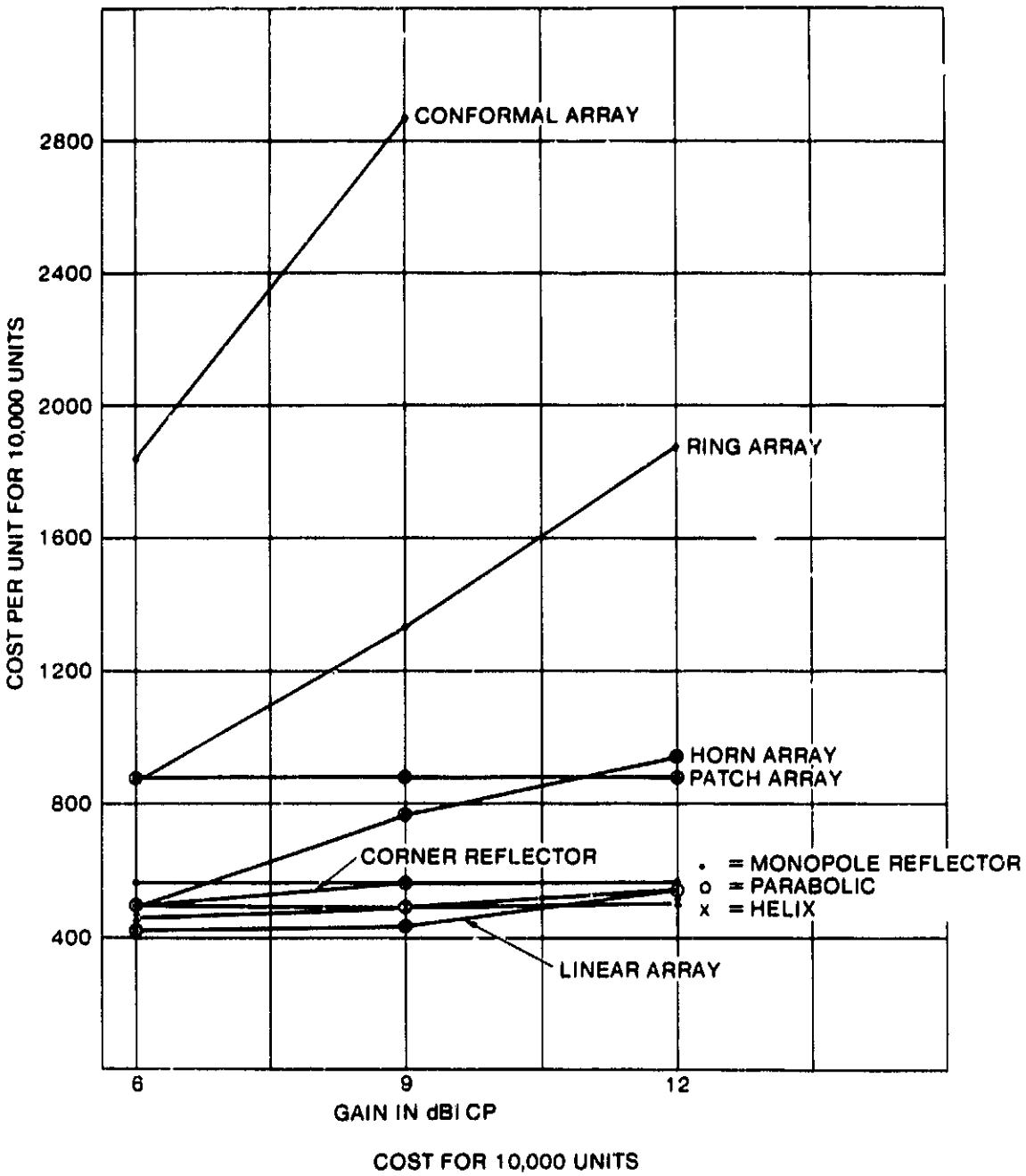


FIGURE 1-2. COST FOR 10,000 UNITS

TABLE 1-1

PERFORMANCE SUMMARY TABLE

	1 X 4 HELIX ARRAY	2 X 5 CROSSED SLOT WITH CORRUGATION	1 X 5 PATCH WITH CORRUGATION	CORNER REFLECTOR WITH CORRUGATION	PARABOLIC REFLECTOR	HORN ARRAY	SWITCHABLE RING ARRAY	CONFORMAL PHASED ARRAY	MONOPOLE ARRAY WITH CORRUGATION
FREQUENCY (TRANSMIT) 821-825 MHz	✓	✓	✓	✓	✓	✓	✓	✓	✓
FREQUENCY (RECEIVE) 866-870 MHz	✓	✓	✓	✓	✓	✓	✓	✓	✓
GAIN (CONUS) (dB)	12	12	12	9	12	12	11	9	9
GAIN (ALASKA + CONUS) (dB)	10	10	10	7	11	11	9	7	7
# ELEV. POSITIONS - (CONUS)	1	1	1	1	SCAN	1	1	SCAN	1
# ELEV. POSITIONS - (CONUS + ALASKA)	1	2	2	1	SCAN	2	1	SCAN	1
VSWR (≤ 2:1)	✓	✓	✓	✓	✓	✓	✓	✓	✓
HPBW - AZIMUTH (DEGREES)	20	20	20	25	26	20	28	17	20
HPBW - ELEVATION (DEGREES)	42	45	40	45	30	50	60	26	45
AXIAL RATIO - CONUS (≤ 4 dB)	5	5	3	3	3	3	3	3	5
AXIAL RATIO - ALASKA (≤ 4 dB)	5	3	3	3	3	3	3	3	5
PATTERN ROLL OFF - 5° (dB)	1	3	3	5	3	3	1	2	5
PATTERN ROLL OFF - 0° (dB)	2	4	4	8	4	4	2	3	8
SIZE - BASE (INCHES)	36	36	36	36	36	36	36	38	36
SIZE - HEIGHT (INCHES)	12	6½	8½	10	24	16	7	1	10
PEAK POWER (100W)	✓	✓	✓	✓	✓	✓	✓	✓	✓
AVERAGE POWER (5W)	✓	✓	✓	✓	✓	✓	✓	✓	✓

(✓) = YES

2.0 INTRODUCTION

The Experimental Mobile Satellite Program Studies have been undertaken by JPL and NASA to provide a needed communication link for rural areas. The M-SAT(X) Program provides land mobile telephone and computer data communications from vehicles located anywhere in the continental United States and Alaska to any other place in the world.

The Land Mobile Station consists of a vehicle-mounted transceiver and rooftop antenna. The link is to a synchronous satellite and from the satellite to a fixed-station telephone gateway. The key system element is the feasibility of the vehicle's rooftop antenna. Since the mobile antenna performance determines the design of the remaining equipment, this study was undertaken to develop baseline antenna designs for the M-SAT(X) Program. The mobile antenna feasibility is not based solely on technical performance such as gain, beamwidth, size and frequency of operation, but also on the aesthetic acceptability of the roof-mounted antenna. Low cost is essential for this mass marketed system.

3.0 STUDY OBJECTIVES

This study is to develop nine antenna concepts suitable for the Land Mobile Satellite Communication System. The antenna will be capable of rooftop mounting on all automobiles or trucks and have minimum height to reduce aerodynamic drag and to allow the car to fit into every garage. The antenna is to be aesthetically pleasing and inexpensive. The cost of each concept is to be estimated for 100 and 10,000 units.

In addition to these consumer driven requirements the antenna must perform in a satellite data link having stringent technical performance requirements which assure reliable communications. The communication system requirements depend heavily on the practical limitation of the landmobile antenna.

Candidate antennas will have gains from 6-to-12 dBCP to allow trade-offs of satellite antenna gain transmitter power and number of beams. The polarization has been chosen to be circular since the Faraday effect can cause polarization conversion if linear polarization is used.

Detailed technical requirements follow.

The following antenna performance specifications shall be met.

For communications between the satellite and land mobile vehicle, the vehicle antenna shall have its beam directed toward a geostationary satellite whenever the communication link is turned on. The antenna could be an omnidirectional design or a pencil beam design with tracking capability. In the tracking design case, the antenna shall first acquire the satellite and continue tracking it while the vehicle is in motion. The acquisition and tracking shall preferably be automated so that it requires minimal or no intervention from the user.

The satellite shall provide a signal to cover CONUS at all times within the frequency bands stated below. If the proposed system requires a specific signal structure from the satellite for the purpose of acquisition and/or tracking, such a signal structure shall be determined.

(1) Frequency

The antenna shall operate at transmit frequency band from 821-to-825 MHz and simultaneously at receive frequency band from 866-to-870 MHz. The antenna may operate in separate bands or in a continuous band from 821-to-970 MHz. Diplexing the transmit and receive frequencies shall not be a part of this study.

(2) Gain

The required gain at the antenna input (feed circuit losses have been subtracted) is allowed to vary between 6 dBic minimum and 12 dBic minimum for different antenna designs. For each antenna design, the required minimum gain (not necessarily the antenna peak gain) shall be directed toward the satellite at all times.

(3) Beam Pointing Accuracy

Not specified with the condition that the required gain (not necessarily the antenna peak gain) shall always be directed at the satellite.

(4) Coverage

The antenna shall provide either a directive or nondirective beam with a gain as indicated in paragraph (2). This is required to communicate with the satellite located in the following coverage region with respect to the mobile vehicle for users in both Continental US (CONUS) and Alaska: full azimuth coverage of 360° and minimum elevation coverage from 10° to 60° from the horizon. If the coverage in elevation is not possible with one antenna, the use of two separate antennas is permissible. In this case, one antenna shall cover 20° to 60° from the horizon for CONUS users only and the other shall cover 10° to 20° from the horizon for Alaska users only. Both antennas shall have full azimuthal coverage.

(5) Voltage Standing Wave Ratio (VSWR)

Each antenna shall have an input VSWR of 2:1 or less throughout the specified operating frequency bands.

(6) Beamwidth

Not specified with the condition that it shall not create problems to the acquisition and tracking of the satellite.

(7) Polarization

The antenna shall provide circular polarization (sense of polarization is not important at this study stage) with an axial ratio of 4 dB or less within the specified coverage region and frequency bands. If 4-dB axial ratio is not realistic for certain antenna concepts, the Contractor shall provide adequate justification and generate a more realistic value.

(8) Sidelobe Level

Not specified with the condition that the ground multipath effect shall be minimized. The required radiation level at elevation angle of 5° from horizon and lower shall be at least -7 dB down from the required minimum gain. The radiation level shall also be at least -10 dB from the required minimum gain at elevation angle of 0° and lower. These radiation levels will be achieved with the antenna mounted on a vehicle with its associated ground plane having the dimensions stated in paragraph (9). If these radiation levels are not realistic for certain antenna concepts, the Contractor shall provide adequate justification and generate more realistic numbers.

(9) Size

For a conformal type of antenna, the radiators and the electronics or other control devices shall be confined to a flat area of approximately 38 inches

diameter or smaller and approximately 3.0 inches or less thickness. For a nonconformal type of antenna, the antenna shall be confined in a horizontal area of approximately 36 inches or less in diameter. Height shall be kept low so that it does not impede the normal operation of the car. It shall have enough structure strength under severe road vibration and/or wind conditions that there shall be no significant degradation to the antenna performances and damage to the antenna.

(10) Weight

Not specified with the condition that it shall not overburden the mobile vehicle's performance.

(11) Power Handling Capability

The antenna shall be able to transmit a peak power of 100 watts and average power of 5 watts.

(12) Radome

The antenna shall be protected from rain, snow, wind and other adverse weather conditions (such as with a thin layer of radome material). All the antenna performance requirements specified in paragraphs (1) through (11) shall include the effects of this protective material.

(13) Technology Cutoff Date

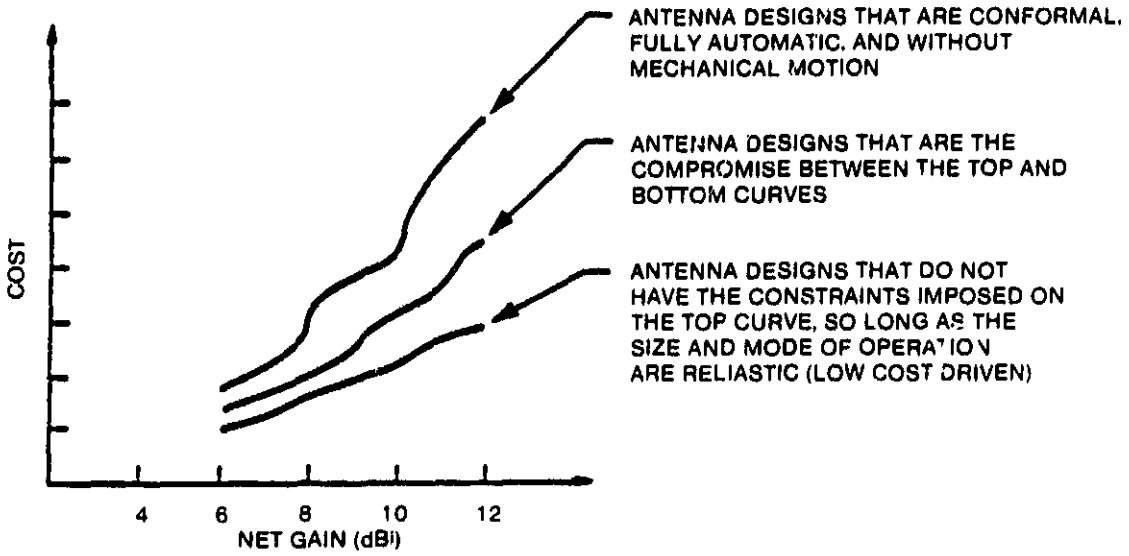
Any future technology or component used in the design of these antenna systems shall become realizable prior to the end of year 1984. If the Contractor feels a concept requiring future technology is desirable, the Contractor shall specify the concept and the maturity time of the technology.

3.1 Cost Estimate Requirements

(1) For this Contract, the antenna gain is allowed to vary in the range from 6 dBic minimum to 12 dBc minimum for different antenna designs. The cost estimate versus antenna gain for different antenna designs shall be generated. Three cost-versus-gain curves shall be generated (see Figure 3-1). One, on top of the cost scale, consists of antennas conformal to the roof of the vehicle that are fully automated and require no user intervention, and have no mechnical motion with respect to the vehicle. The other, at the bottom of the cost scale, consists of antennas that do not have the constraints as imposed on those of the top curve so long as the size and operation do not become unrealistic. The third curve, in the middle of the cost scale, consists of antennas that represent the compromise between the top and bottom curves in terms of degrees of conformity, user intervention, and mechanical motion.

(2) Each of the above curves, in the ranges of 6 dBic to 12 dBic, is formed by connecting several discrete points which correspond to different antenna designs. In generating these curves, it is important to concentrate on regions where a change in gain results in substantial change of cost. There shall be a minimum of three points for each curve. Two shall be the two extremities of the curve, i.e., antenna designs with 6 dBic and 12 dBic of gain. The third point shall be where there is a sudden change in cost, specifically where the cost is the lowest. In the case that a curve does not show any sudden cost change, the third point shall correspond to a design with 9 dBic of antenna gain.

(3) The cost for each antenna system shall be kept as low as possible and shall be in 1983 dollars based on manufacturing in the following two different quantities: (1) approximately 10-thousand units manufactured in a 3-year period and (2) approximately 100 units manufactured in a 1-year period. The cost estimate shall include the radiators as well as the feed and control circuits such as phase shifters, power dividers, microprocessor, compass, servo-motor, and/or other appropriate devices.



- STUDY THE DESIGN AND COST IMPACT OF TWO SPECIFIC ANTENNA CONCEPTS FROM THE ABOVE CURVES

FIGURE 3-1. EXAMPLE OF COST-VERSUS-GAIN FOR VARIOUS MOBILE ANTENNA DESIGNS.

3.2 Design Changes

(1) The antenna shall be able to acquire and track one satellite in a two-satellite system. For the purpose of this study, the two satellites are to be located at 80° and 113° longitude in the geostationary orbit.

(2) The antenna shall still produce a single beam; however, while this beam is directed toward one satellite, it requires the antenna to radiate a negligible field in the direction of the other satellite or vise versa. The isolation between the two satellites shall be 20 dB minimum. If 20 dB isolation is not achieveable by radiation pattern alone, part of this isolation may be achieved by polarization diversity or other appropriate techniques. This condition shall hold for a vehicle anywhere in the Continential US (CONUS).

4.0 CANDIDATE ARRAY ELEMENTS

This study was organized by breaking the tasks into basic design elements. These are the array elements, arraying systems, scanning techniques, and tracking methods. In some cases long lists of potential design elements were made so that no possible design concept would be overlooked. This was particularly true of array elements and array systems. Each design facet was carefully studied for suitability. The suitable design elements were then put together into a system in the section on selected systems.

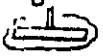
The range of gain from 6-to-12 dBcp precludes the use of simple antennas, necessitating the arraying of several simple antenna elements to achieve the required gains. The elevation radiation pattern performance of the array element adjacent to the ground plane is crucial to the design. A list of potential array elements was made. Since the study is to focus on nine antennas, the selection field must, of necessity, be very large. As a consequence, every conceivable antenna array element was listed as a potential study candidate. The result is Table 4-1 where the antennas are listed by generic type, description, pictorial, and beam characteristics.

Early in the study it was believed the primary effect of the antenna ground plane, or vehicle roof, would be to degrade the circular polarization at the low elevation angles. Degradation was expected because the propagation of parallel polarized electromagnetic field is not favored along the conducting ground plane.

It is desirable to position the radiation peak at 40 degrees elevation while maintaining a symmetrical elevation beam shape. The beam will then fit the requisite coverage area. Unfortunately, the peak beam position is determined by the ground plane length in front of the antenna, the height of the antenna above the ground plane, and the orientation of the antenna with respect to the ground plane.

These factors make elevation radiation pattern the dominant factor in obtaining the required gain. Consequently the design of the array element for the elevation pattern was the first priority of this study. The list of candidate array elements was reviewed and antennas were selected for their inherently good coverage of the critical low angles. In Table 4-1 the array elements having one asterisk were identified as the most likely candidates. The following section will discuss each candidate array element in turn.

TABLE 4-1. POTENTIAL ARRAY ELEMENTS

GENERIC ANTENNA	DESCRIPTION	PICTORIAL	PATTERN
1 DIPOLE	1.1 CROSSED "V" DIPOLE (CONVENTIONAL)		HEMISPHERE
	1.2 CROSSED DROOPY DIPOLE		HEMISPHERE
	1.3 CROSSED V DIPOLE WITH SHORTENED ORTHOGONAL ELEMENT		HEMISPHERE
	1.4 SHAPED MONOPOLE		BI-DIRECTIONAL
	1.5 LINDEN BLATT		HEMISPHERE
	1.6 CORNER REFLECTOR		UNIDIRECTIONAL BEAM
2 LOOP/SPIRAL	2.1 AXIAL MODE HELIX		UNIDIRECTIONAL BEAM
	2.2 IMAGED AXIAL MODE HELIX		UNIDIRECTIONAL BEAM
	2.3 CONICAL SPIRAL		HEMISPHERE
	2.4 PLANAR SPIRAL		
	ARCHIMEDIAN		UNIDIRECTIONAL
	LOGARITHMIC		UNIDIRECTIONAL
	2.5 NORMAL MODE HELIX		MONOPOLE OMNI
	2.6 KILGUS NORMAL MODE HELIX (QUADRA FILLIAR HELIX)		MONOPOLE OMNI
	2.7 HULA HOOP		MONOPOLE OMNI
3.0 SLOT	3.1 CROSSED SLOT WAVEGUIDE		UNIDIRECTIONAL
	3.2 INTERRUPTED COAX LINE VERTICAL MOUNT		MONOPOLE OMNI
	3.3 SLOT MONOPOLE		BI-DIRECTIONAL
	3.4 SLOT FOLDED DIPOLE		BI-DIRECTIONAL
4 APERTURE ANTENNAS	4.1 HORN/WAVEGUIDE		UNIDIRECTIONAL BEAM
	4.2 POLY ROD		UNIDIRECTIONAL BEAM
	4.3 REFLECTOR		
5.0 CONFORMAL	5.1 CROSSED SLOTS		BEAM TOWARD ZENITH
	5.2 STRIP		BEAM TOWARD ZENITH
6.0 SPECIAL TECHNIQUES	6.1 POLARIZATION GRATINGS		CONVERT LINEAR TO CP
	6.2 ABSORBER		CONTROL REFLECTION

4.1 Dipole Type Antennas

The crossed "V" dipole, the crossed droopy dipole and the crossed "V" dipole with shortened orthogonal elements are considered one generic antenna element class in Table 4-1. This class of antennas is known to have very good patterns and axial ratio at the critical low angles. The radiating elements are "V" shaped, hence no nulls occur along the axes of the elements giving good pattern coverage on the horizon. The antenna is elevated above the ground plane giving good parallel polarization along the ground producing excellent axial ratios on the horizon as well as zenith. The shortened orthogonal V dipole is the lowest cost of the dipole antennas since it does not require a 90 degree hybrid circuit. A picture of the shortened dipole antenna is shown in Figure 4.1-1. Circular polarization requires spatially orthogonal elements fed in quadrature phase. The shortened elements are connected to opposite feed lines of the balun along with the longer elements. The longer and shorter elements are fed 180 degrees out of phase. The short elements are shortened to provide a 90-degree phase shift in the feed current providing the 90 degree phase shift required for circular polarization. The measured scale model patterns are shown in Figure 4.1-2. The patterns show the antenna to have poor circularity and unacceptably poor pattern coverage in the lower elevation angles. To be acceptable the gain must be 5.0 dB.

The crossed V dipole was considered next. Figure 4.1-3 is a sketch of the antenna. The droopy dipole was not considered separately because of its similarity to the crossed V dipole. The V dipole requires a 90-degree hybrid to feed the antenna. Scale model pattern measurements were made with various ground plane heights. The optimum radiation pattern is shown in Figure 4.1-4. The results show the low angle elevation gains to be +1 and -1 dBcp for CONUS and Alaska, which are unacceptably low. Both the Γ shaped monopole and Lindenblatt antennas were considered to be impractical. The Γ antenna has questionable polarization characteristics and the Lindinblatt is complex to fabricate.

A corner reflector having its dipole feed rotated about the dipole axis (shown in Figure 4-1) produces circular polarization (Ref. 1). This antenna was investigated because of its simplicity. The measured pattern results show the gain to be unacceptably low.

Ref. 1: Woodward, Jr, O.M.: "A Circularly-polarized Corner Reflector Antenna," IRE Trans., Vol. AP-5, pp. 280-297, July 1957

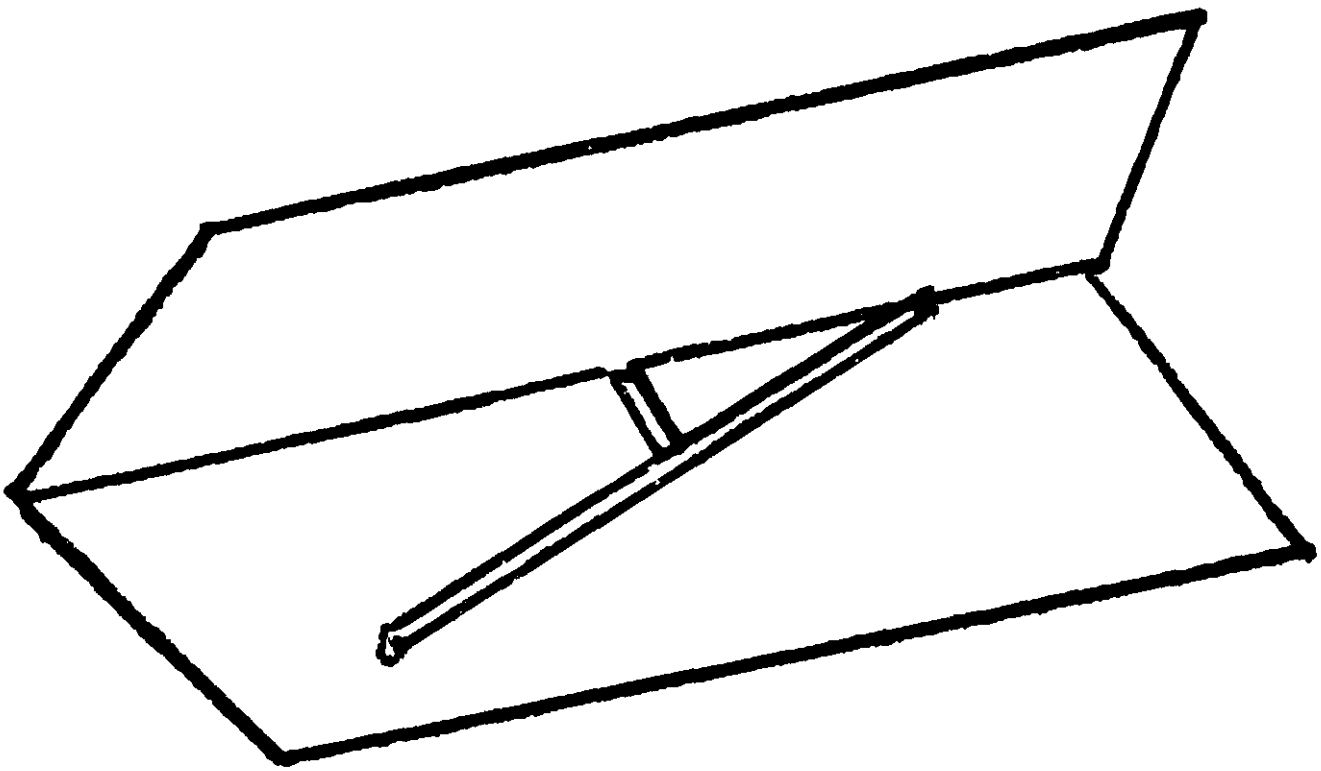


FIGURE 4-1. DIPOLE IN CORNER REFLECTOR

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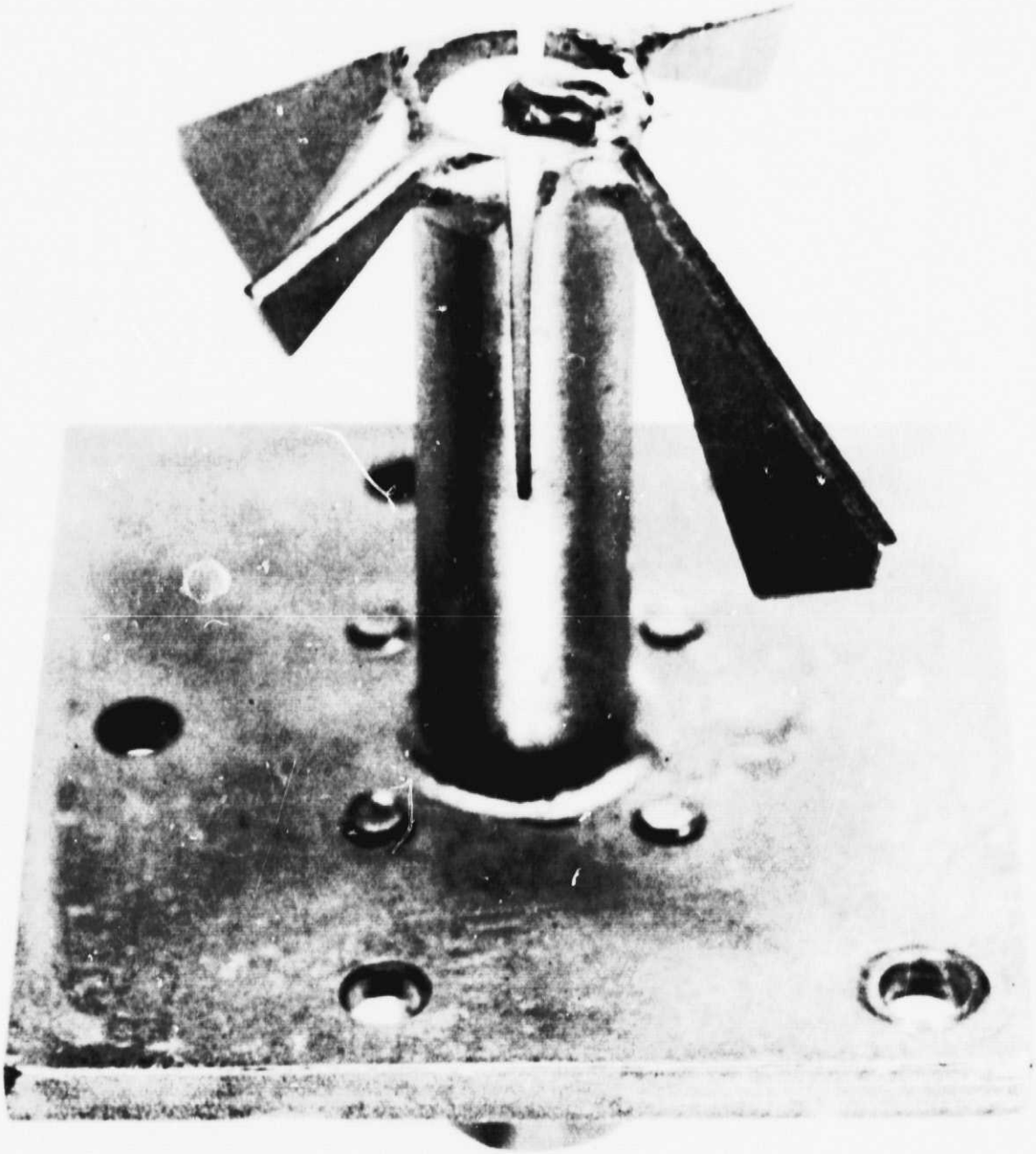


FIGURE 4.1-1. PICTURE OF SHORTENED DIPOLE

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FIGURE 4.1-2. PATTERNS OF ASYMMETRICAL DIPOLE

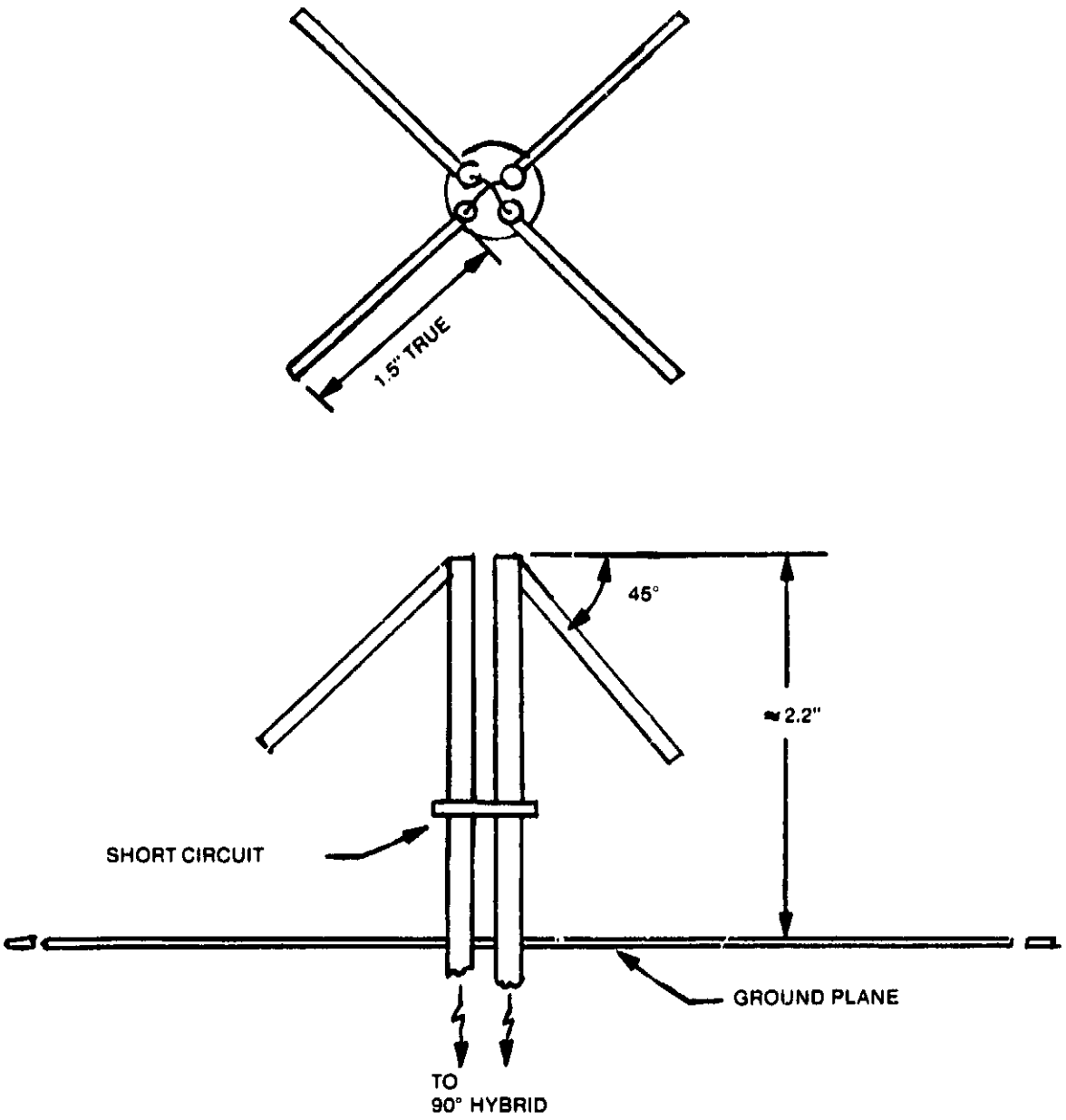


FIGURE 4.1-3. CROSSED "V" DIPOLE ANTENNA

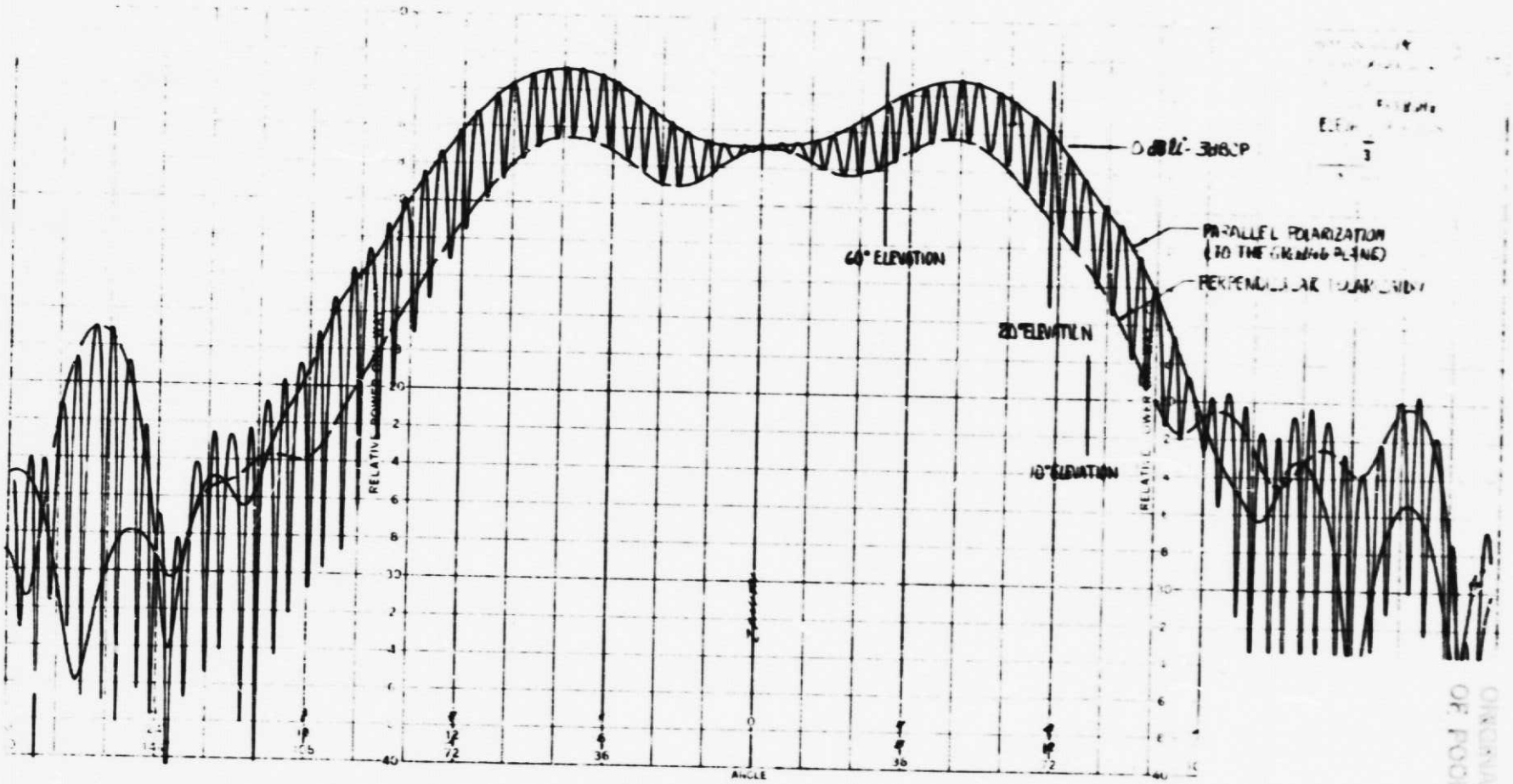


FIGURE 4.1-4. CROSSED "V" DIPOLE RADIATION PATTERN OPTIMUM GOUND PLANE SPACING

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The linearly polarized corner reflector is a simple antenna. Several versions of this antenna were further developed. The first is the vertical monopole in a corner reflector. Although this antenna is vertically polarized, a polarization grating can be used to produce circular polarization. There is considerable literature available for this antenna without a ground plane present. Elevation patterns are very dependent on the ground plane; a scale model was made and antenna performance measured. The performance was good for the 6 dB gain case. However, the required gain fall-off from +5 degrees to 0 degrees elevation was not met. The ground plane controls this feature. The fall-off can be improved by rapidly attenuating the vertically polarized wave along the ground plane. A corrugated surface is an ideal way of producing pattern fall-off. A corrugated surface was designed with 10 dB attenuation from Ref. 2. Corrugation periodicity = 0.525; Tooth width = 0.064; Depth = 1.75 inches. The results were very encouraging. The fall-off at 0 degrees elevation is 9 dB and at 45 degrees is 5 dB. Figure 4.1-5 is a photograph of the scale model antenna. The corrugations will be inclined to reduce the overall antenna height in the final version. A polarization grating was designed from Ref. 3 for the antenna. A test piece polarizer was made for normal incidence angles and excellent orthogonal and wide-angle circular polarization results were obtained. A large grating was fabricated and placed in different positions over the corner reflector. The best result was obtained with a grating thickness of 3 inches on the scale model. This is unacceptably thick for full scale antennas but can probably be made thinner by redesigning the grating for angle of incidence. The scale model grating is shown in Figures 4.1-5 and 4.1-6. The elevation radiation pattern is shown in Figure 4.1-7 for the optimum location of the grating and antenna tilt of 6 degrees.

4.2 Spiral Antenna Types

The selected antennas were the axial mode helix because of its simplicity and the imaged axial mode helix because of its low height. The normal mode helix was chosen

Ref. 2 Mentzer, Carl A., and Peters, Leon.; Properties of Cutoff Corrugated Surfaces for Corrugated Horn Design, IEE Trans., Antennas and Propagation. Vol AP-22, pp. 191-196, March 1974.

Ref. 3 Lerner, David S., A Wave Polarization Converter for Circular Polarization, IEEE Trans., Antennas and Propagation, pp. 3-7, Jan 1965.

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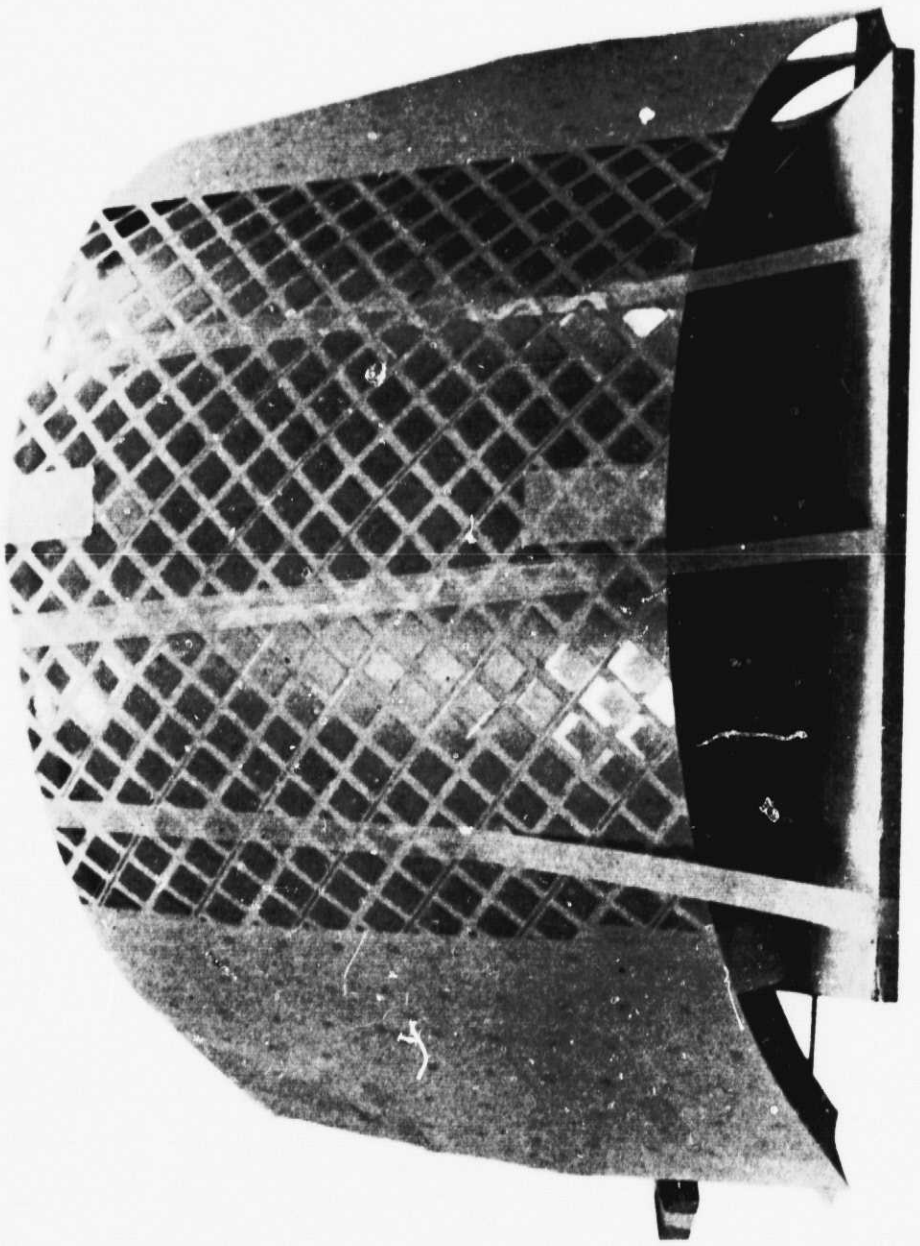


FIGURE 4.1-5. PICTURE OF GRATING AND CORNER REFLECTOR

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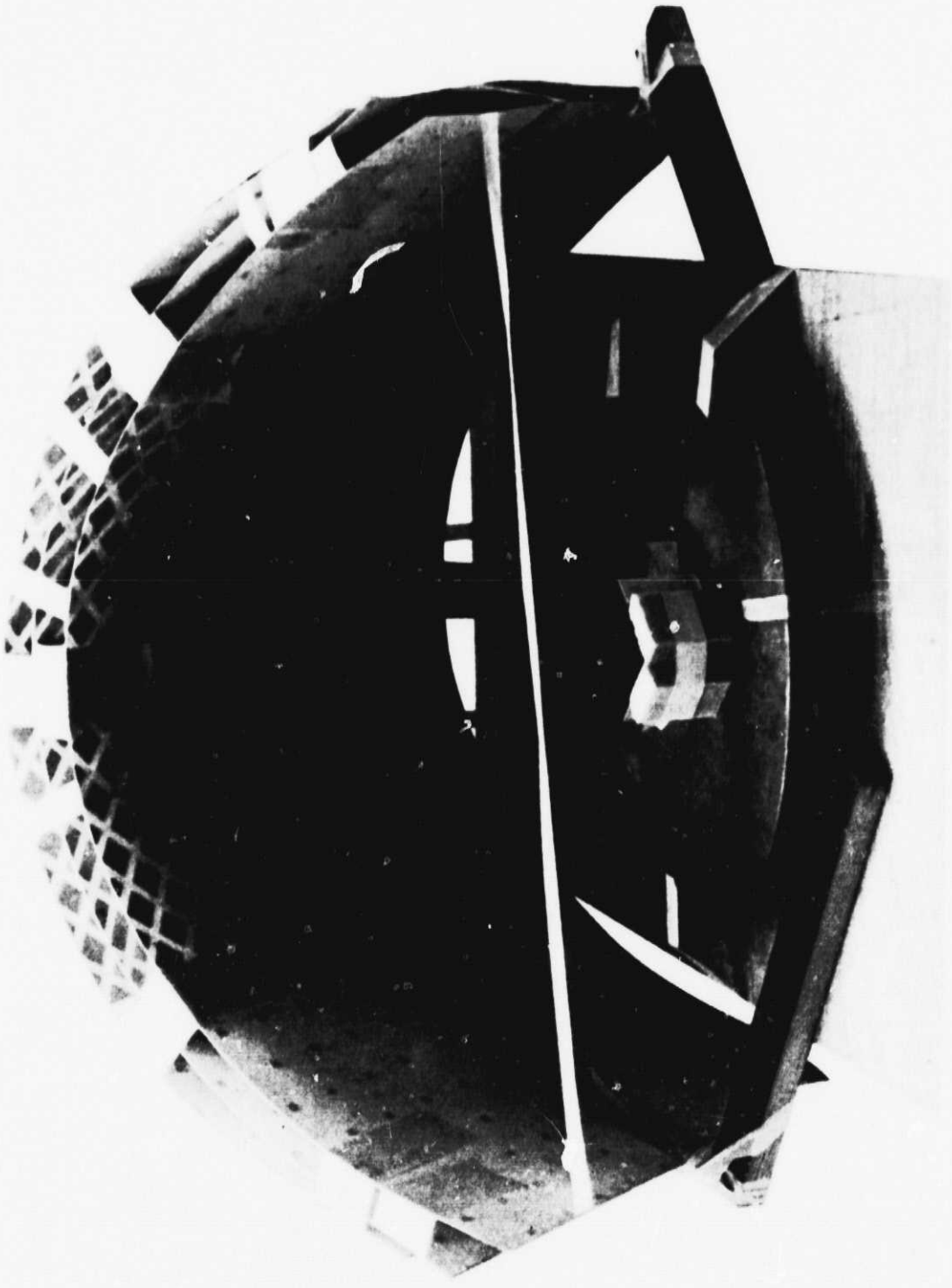


FIGURE 4.1.6. POLARIZATION GRATING AND CORNER REFLECTOR

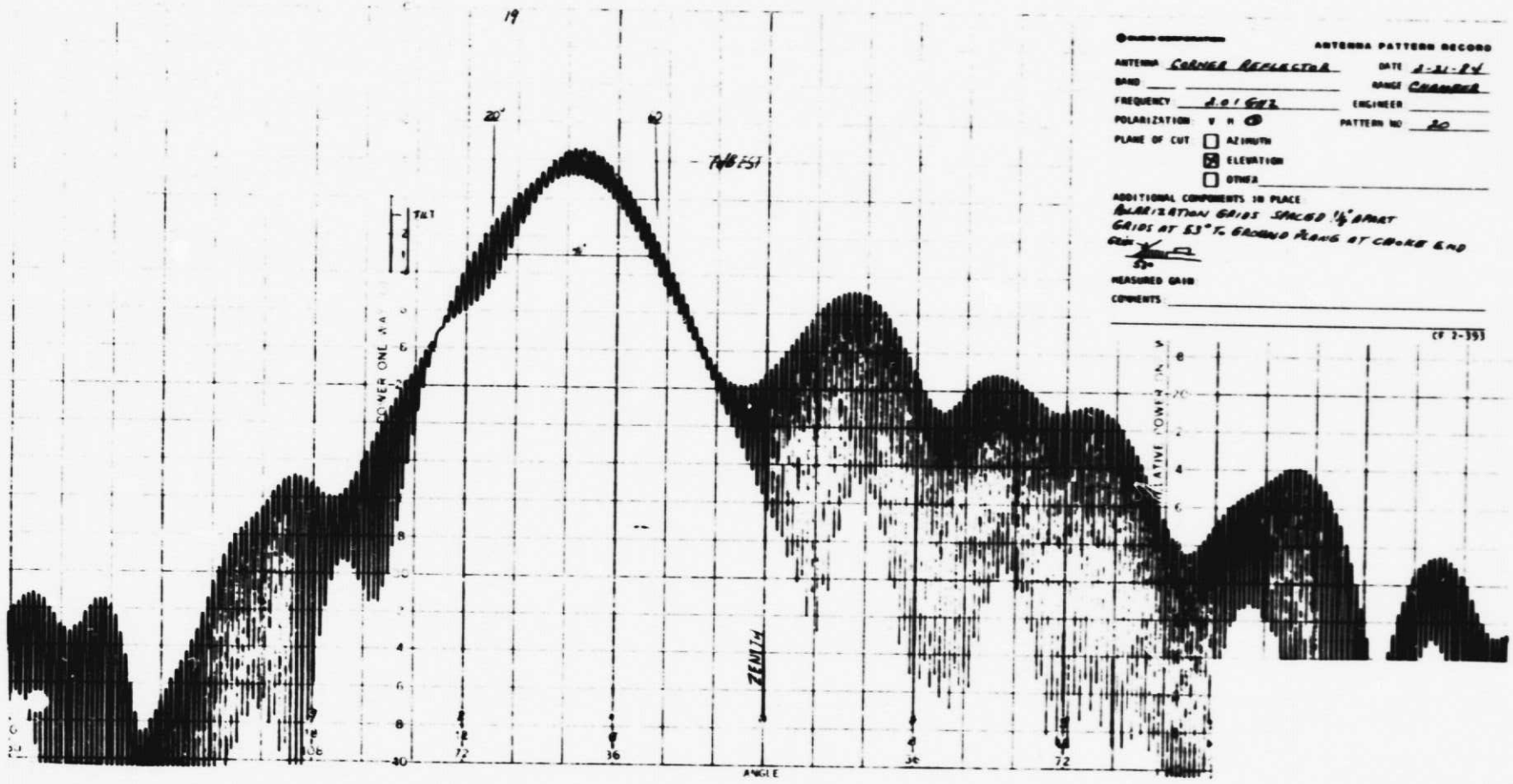


FIGURE 4.1-7. CORNER REFLECTOR AND GRATING

because of its elevation above the ground plane which gives good pattern characteristics on the horizon. The spiral antennas were dismissed because their patterns for normal mounting are directed to the zenith having poor coverage near the horizon. The Hula-Hoop was briefly investigated because of its simplicity and low height but good axial ratios were not obtained.

A scale model axial mode helix was designed and placed over a ground plane. Several configurations were made and the resulting measured radiation patterns were shown in Figures 4.2-1 through 4.2-5. Aligning the helix axis parallel to the ground plane would normally produce a radiation peak at a lower elevation angle. However, this was not the case. As can be seen, performance of the antenna over the ground plane is unpredictable.

The optimum angle was found to be 30 degrees. The circular polarization is better near the plane of the ground plane. This unexpected result is due to a complex interaction of the helix and ground plane. The radiation pattern elevation tilt angle of 30 degrees is excellent. The helix was placed over a corrugated surface to improve its axial ratio at high angles. Improvements of approximately 1 dB were obtained at the expense of detrimental shaping.

The radiation pattern from the imaged axial mode helix was not successful. Circularity was poor and the position of the pattern maximum was also poor. The same results were essentially obtained with the normal mode helix.

4.3 Slot Antennas

The crossed slot waveguide antenna was dismissed as a narrowband antenna with poor coverage near the horizon.

The interrupted coaxial line antenna mounted vertically requires excessive height in order to meet pattern coverage and gain. This is also true for the linear vertical array.

The slot dipole antenna shown in Figure 4.3-1 was investigated (Ref. 4). Slot dipole patterns are shown in 4.3-2. Good circularity and gain are not obtained on the horizon.

Ref. 4 Sidford, M.J., A Radiation Element Giving Circular Polarization Over a Large Solid Angle, IEE, C.P. #95, pp. 18-25, 1973.

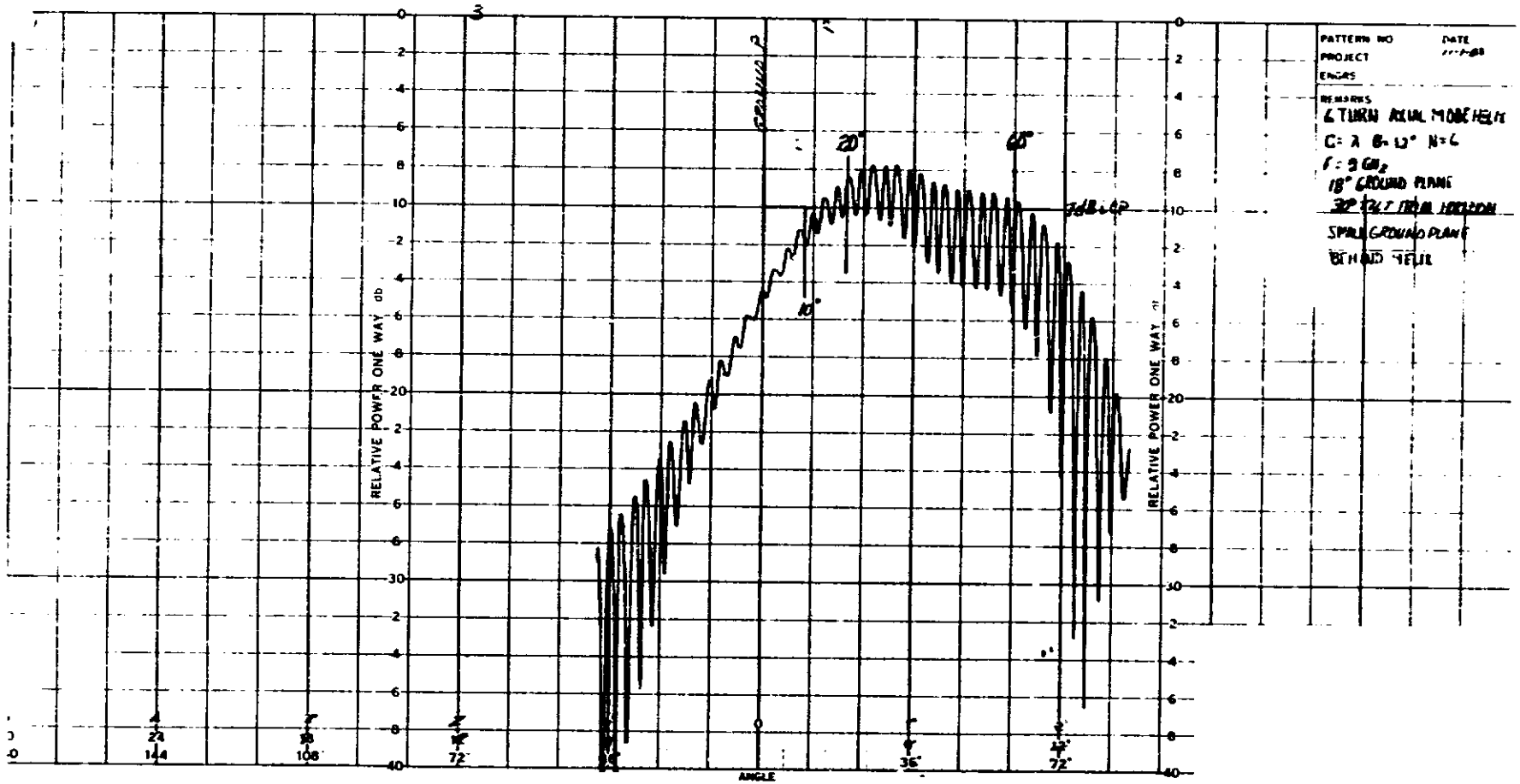


FIGURE 4.2-1. SIX TURN HELIX TILTED 30 DEGREES

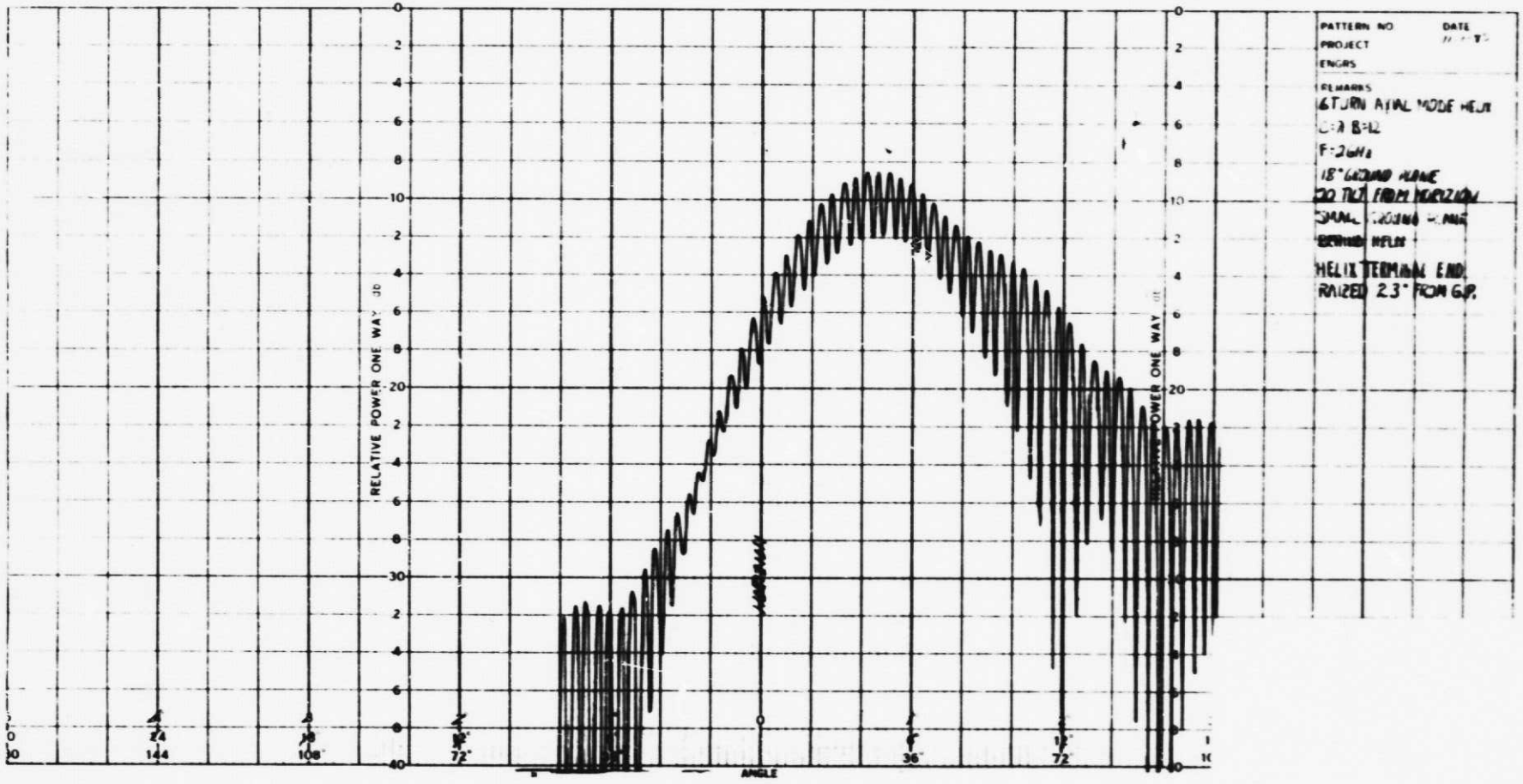


FIGURE 4.2-2. SIX TURN HELIX TILTED 20 DEGREES

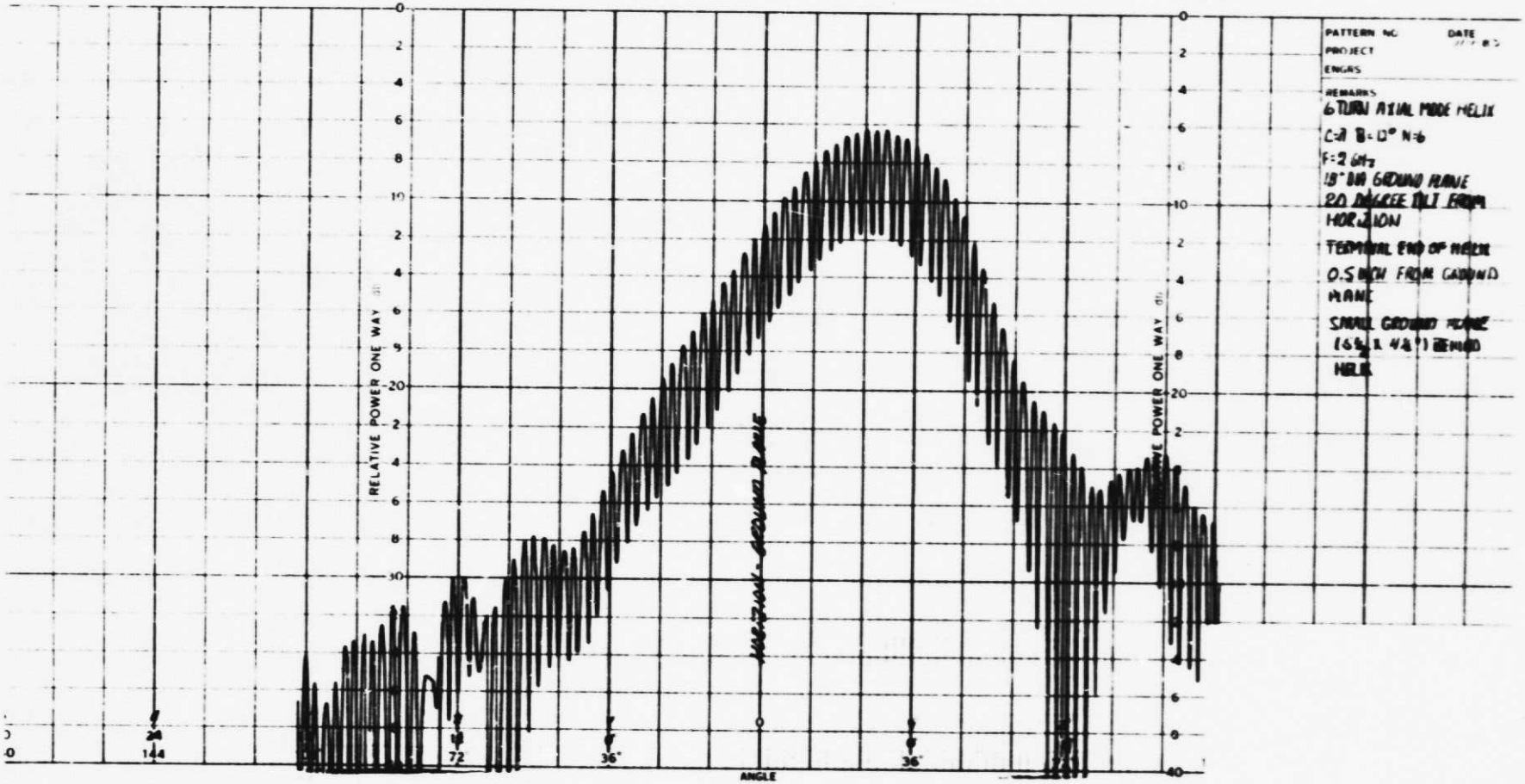


FIGURE 4.2-3. SIX TURN HELIX TILTED 20 DEGREES

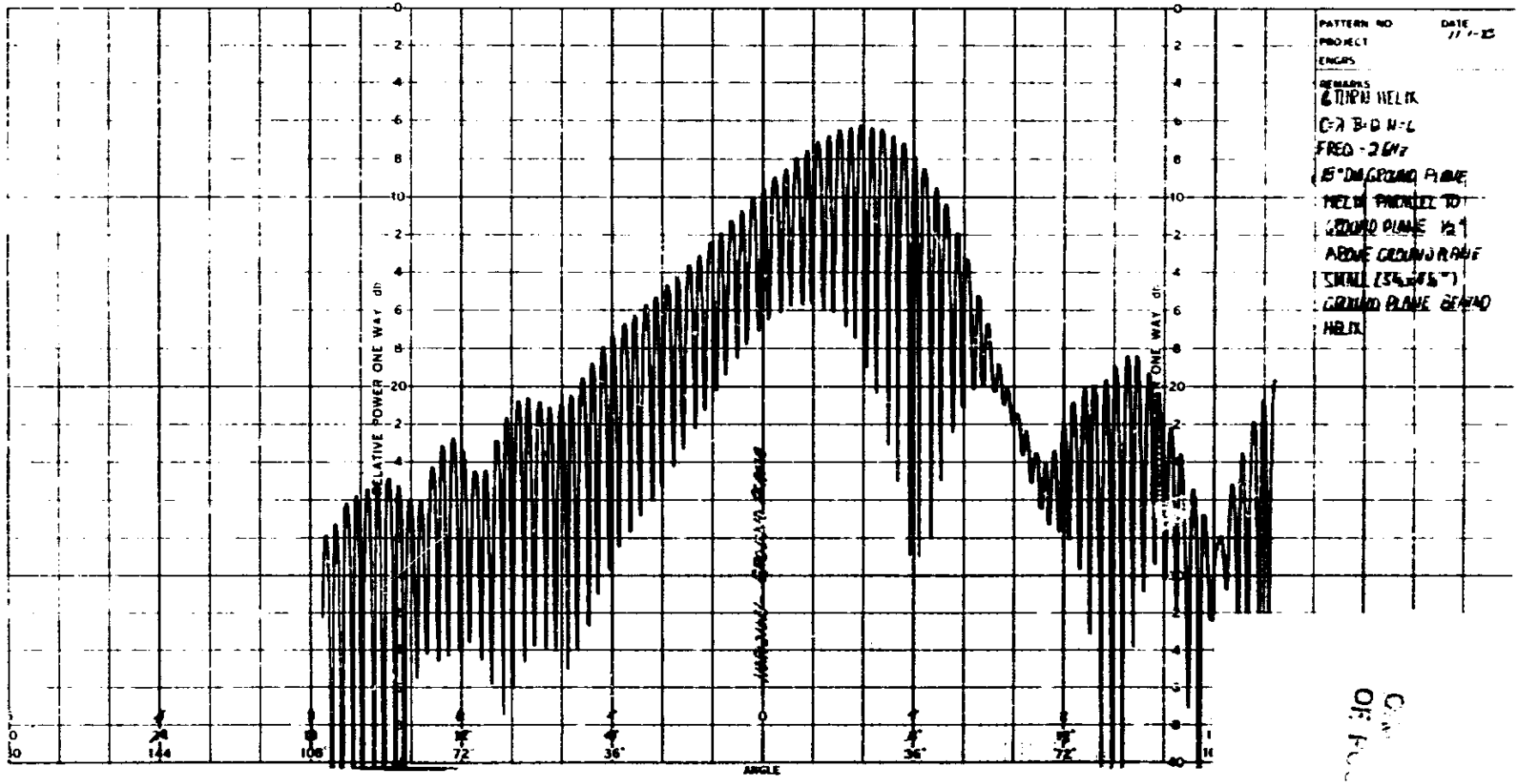


FIGURE 4.2-4. SIX TURN HELIX PARALLEL TO GROUND PLANE

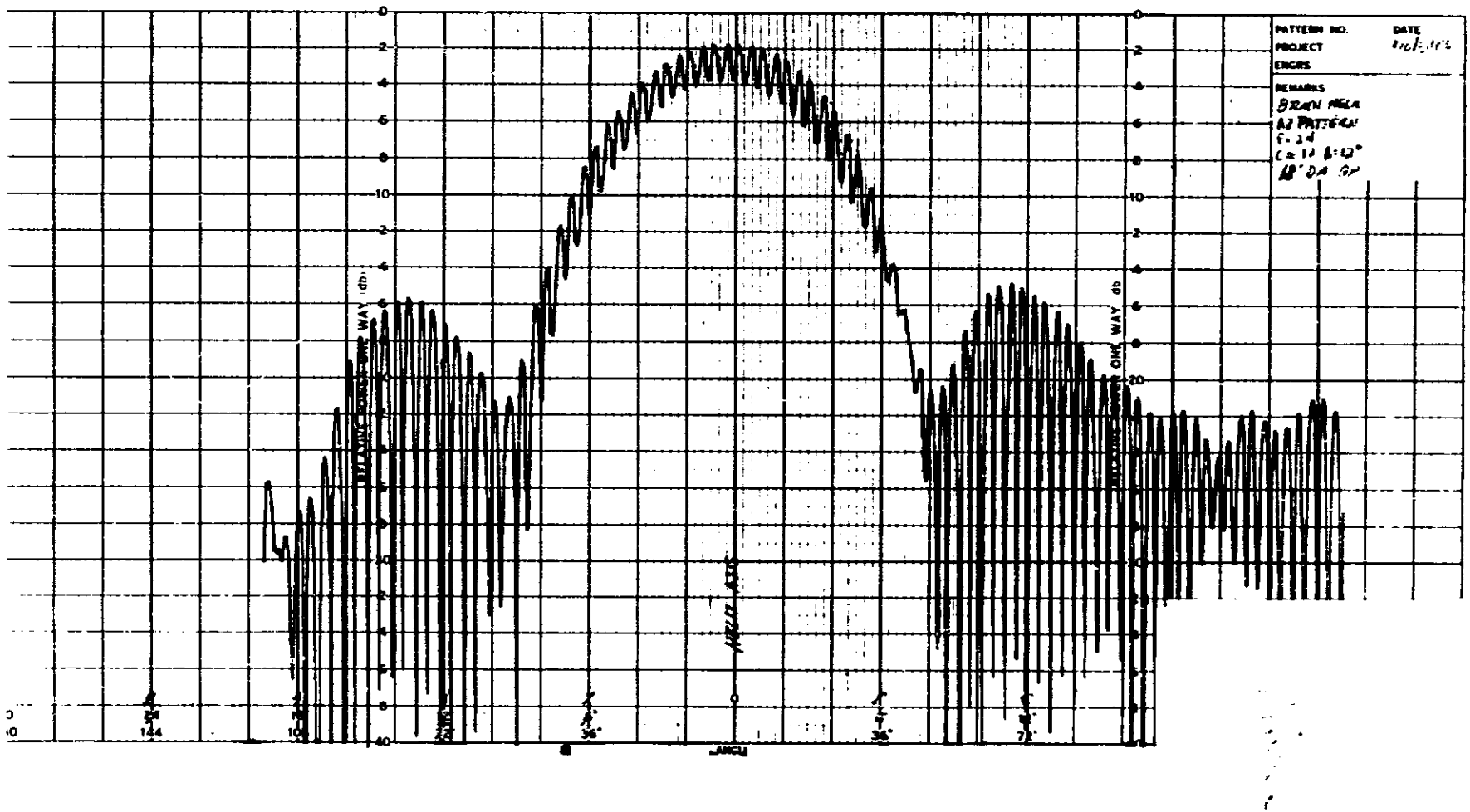


FIGURE 4.2-5. EIGHT TURN HELIX

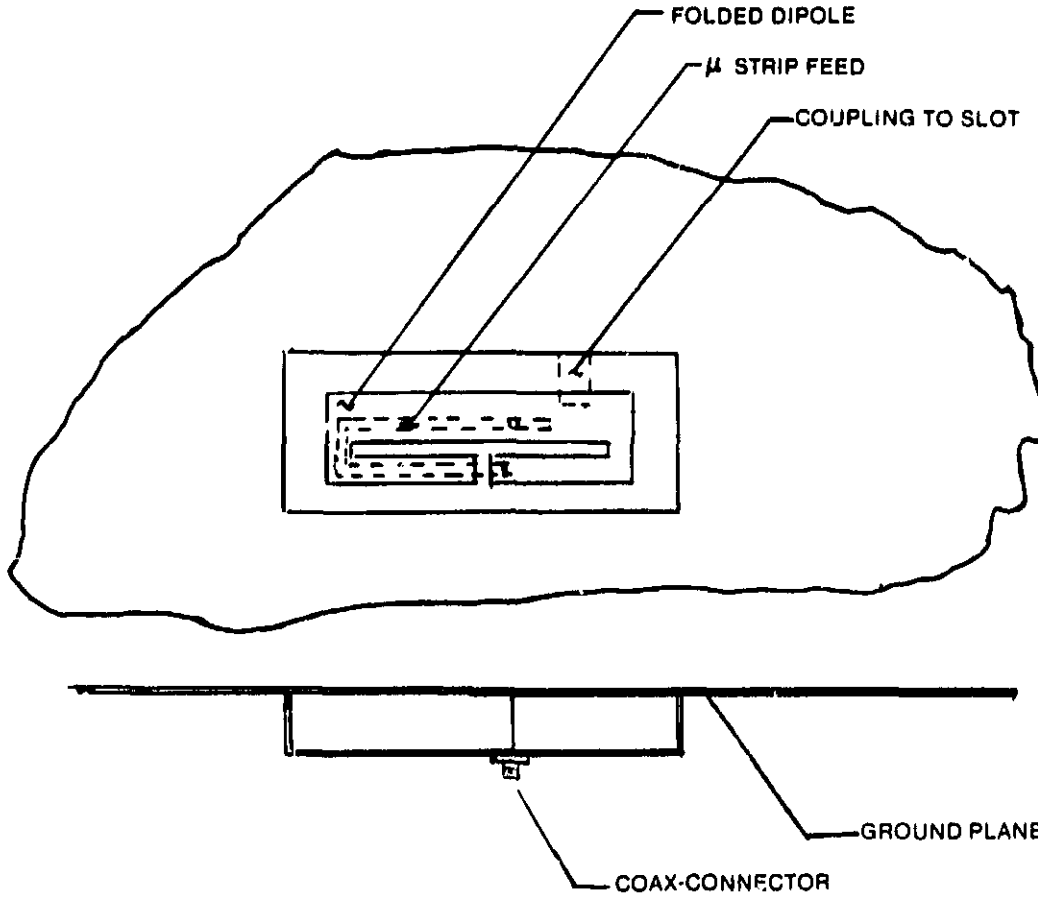


FIGURE 4.3-1. SLOT DIPOLE RADIATOR

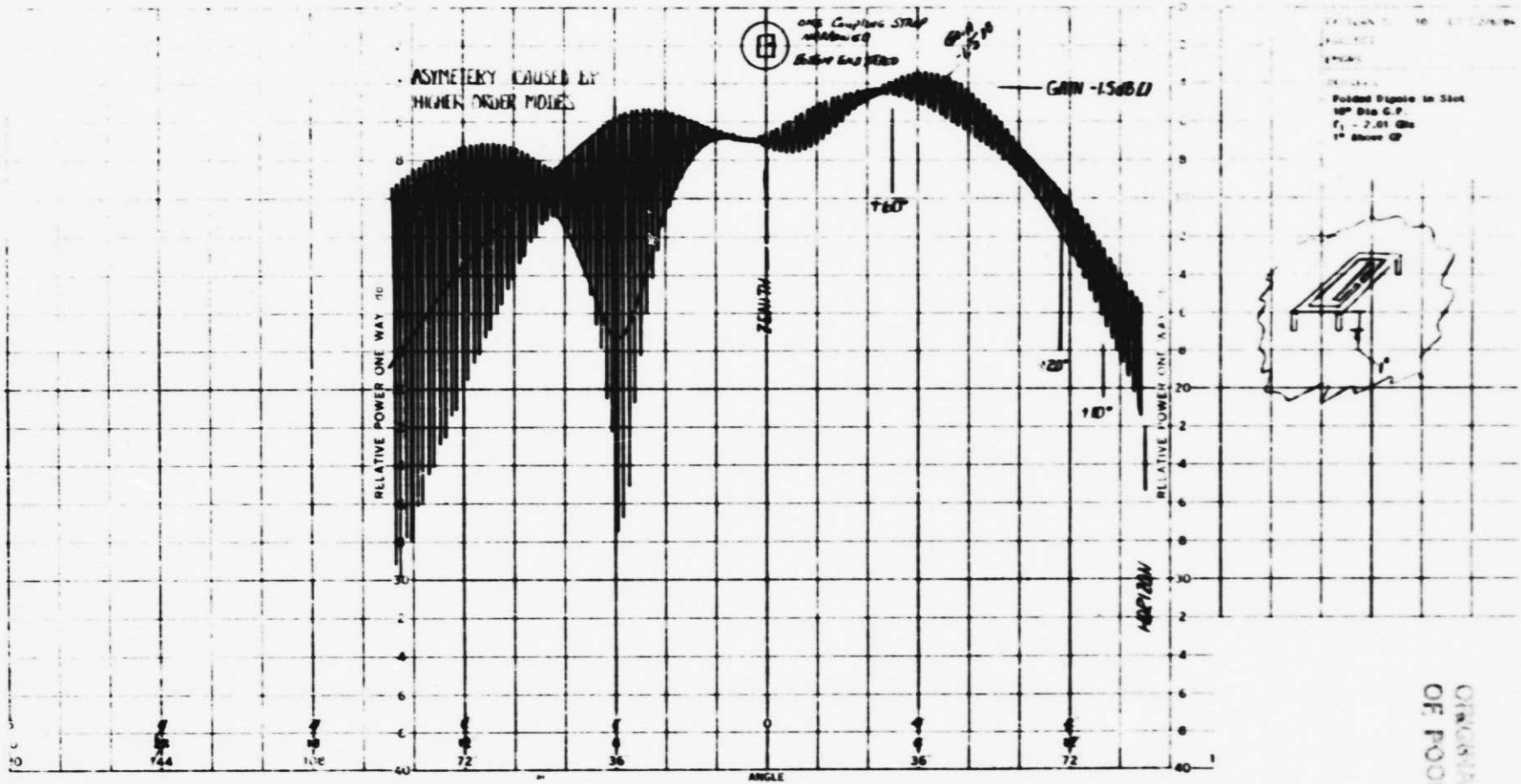


FIGURE 4.3-2. SLOT DIPOLE ELEVATION PATTERN

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4.4 Aperture Antennas

The elevation radiation patterns for the HORN antennas were emperically studied. The large aperture above the ground plane will result in satisfactory patterns particularly if the aperture size is increased and a switchable elevation scanning method is used to optimize the radiation pattern in elevation.

The reflector antenna is an aperture antenna similar to that of the horn and can be expected to have similar performance charactertics.

4.5 Conformal Antenna

The conformal aspect of antenna design requires the antenna to be of low height such as obtained with strip line or microstrip antennas. These antennas have their main beam radiation pointed to the zenith. The radiation then decreases toward the critical horizon area by the element factor and the reduction in projected area with scan angle. For this reason the element radiation pattern must be exceptionally wide to acquire the required low angle coverage. Antennas similar to the crossed-slot antenna have this wider coverage compared to the microstrip patch antenna. This is particularly true for low Q microstrip antennas which have little dielectric loading. Pattern measurements of a crossed slot antenna without a ground plane is shown in Figure 4.5-1.

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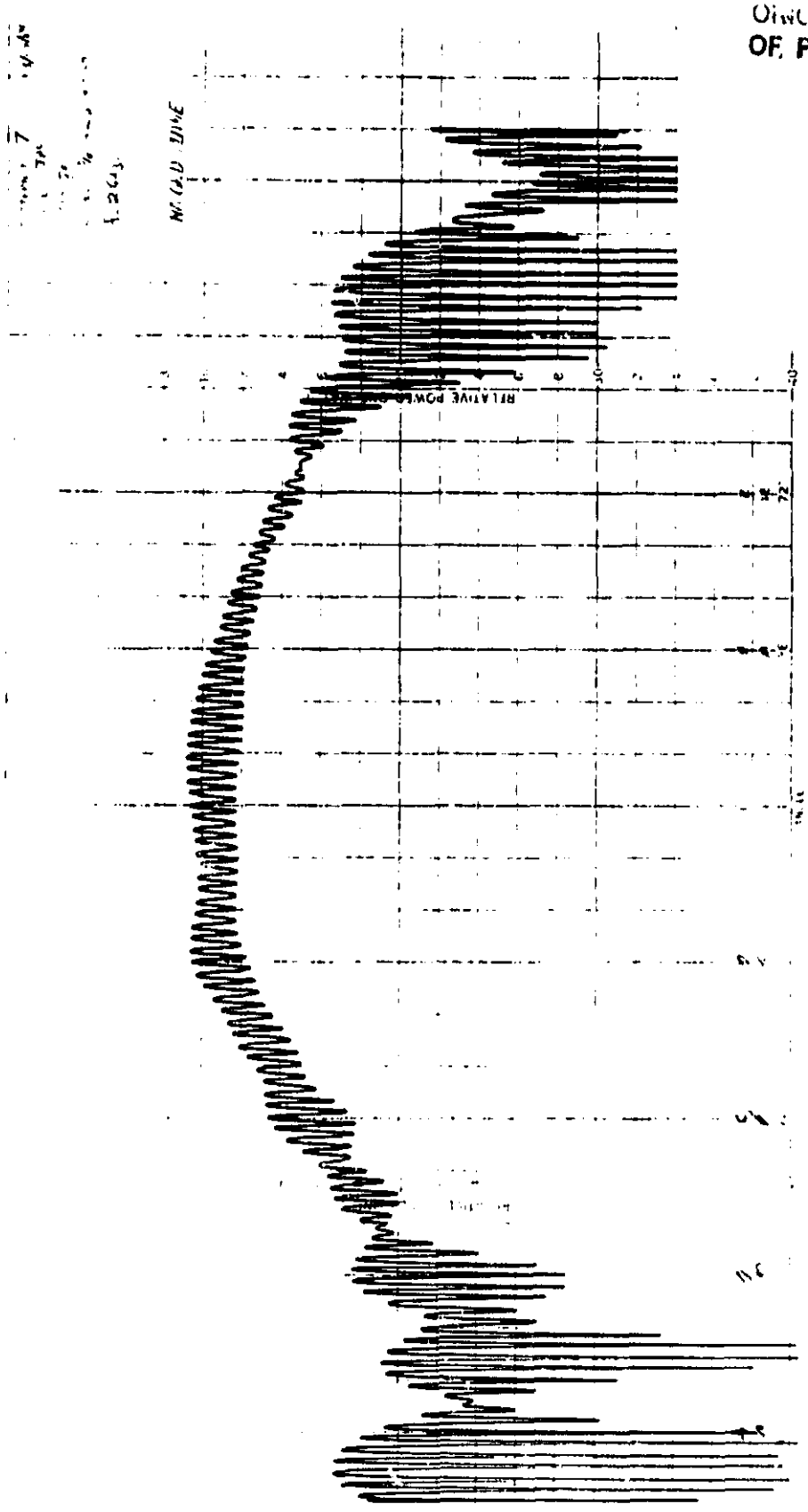


FIGURE 4.5-1. CROSS SLOT ANTENNA

5.0 POTENTIAL ARRAYING TECHNIQUES

This section outlines methods of arraying the basic elements discussed in the previous section into a combination of elements to provide the required gain. The potential arraying techniques are shown in Table 5-1.

5.1 Colinear Array

The colinear array of stacked elements will be excessively high.

5.2 Linear Array

A linear array is a simple antenna array with elements phased to produce broadside or end-fire beams. End-fire antennas are directive in both elevation and azimuth, resulting in a beam that is too directive in the elevation plane. The broadside linear array can be combined with many of the array elements discussed previously to produce antennas of varying gain. The antennas chosen for this are presented in detail in Section 6.0. Scanning the linear array electronically in azimuth results in a reduced antenna gain as the antenna is scanned toward end-fire. This reduction in gain is a cosine function of the scan angle from broadside and there is little gain at end-fire. Placing two arrays in a cross, and switching from one to the other, does not improve the expected gain significantly. Adding more "spokes" to the cross degenerates into the conformal array case. The linear broadside array can be scanned simply by a motor drive.

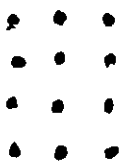
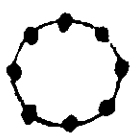
5.3 Planar Array

The planar array lends itself to the conformal array. It requires many phase shifters to scan the beam in the azimuth and elevation angular direction.

5.4 Ring Array

The ring array is a series of elements spaced on the circumference of a circle. Each element must have phase correction in order to scan the beam and to produce an array with low quadratic-like phase errors. This can be accomplished by phase shifters or by mechanically switching. It has a potential for low height.

TABLE 5-1. POTENTIAL ARRAY CONFIGURATIONS

TYPE	CONFIGURATION	COMBINATION
1.0 COLINEAR		COLINEAR · LINEAR PLANAR RING
2.0 LINEAR		
3.0 PLANAR		
4.0 RING		
5.0 SURFACE-WAVE		

5.5 Surface Wave

The surface wave arraying technique was rejected because of weight.

6.0 SCANNING TECHNIQUES

One antenna e. ·nt is not adequate at even the lowest gain for the required coverage. An array of several elements will provide the required gain within the coverage area but requires the beam to scan. A list of potential scanning methods is shown in Table 6-1. There are essentially two scanning modes--elevation and azimuth.

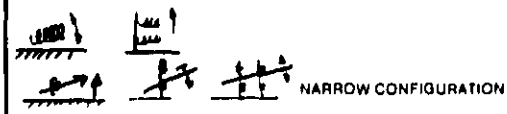
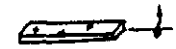
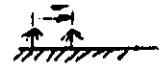
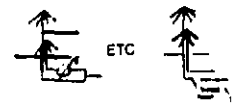
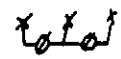
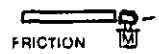
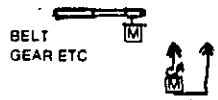
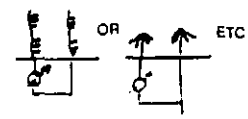
6.1 Elevation Scanning

There are four elevation scanning techniques: (1) mechanically tilting the antenna; (2) changing the spacing between elements; (3) changing the spacing of the ground plane; and (4) changing the phase between elements. Each method, with the exception of changing the spacing between elements, has been used in the candidate system.

6.2 Azimuth Scanning

A practical scheme for azimuth scanning is a simple rotation of the antenna, although electrically scanning or switching can also be used. The best example of electrically scanning will be used in the conformal array discussed in later sections.

TABLE 6-1. POTENTIAL SCANNING TECHNIQUES

SCAN MODE	METHOD	APPLICABLE ANTENNAS	CONFIGURATIONS
1.0 ELEVATION	1.1 MECHANICAL		
	1.1.1 TILTING	AXIAL HELIX	 NARROW CONFIGURATION
		NORMAL MODE HELIXES & LOOPS	
		CORNER REFLECTOR	
		HORNSLOPENEDED WAVEGUIDE	
		SLOTTED WAVEGUIDE	
		INTERUPTED COAXIAL LINE	
		POLY ROD	
	1.1.2 CHANGING SPACING	ALL DISCRETE ELEMENTS OF 1.0 THRU 2.0	
	1.1.3 GROUND PLANE SPACING	ALL DIPOLES SPERHAPS NORMAL MODE HELIXES	
	1.2 ELECTRICAL PHASE SHIFTERS OR SWITCHES	ALL STACKED ARRAYS OF PARAGRAPHS 1.0 THRU 2.0	 ETC
		VALUE GUIDE	 DITTO
		CROSS SLOTS/IMAGED AXIAL MODE HELIX (SLOT/MONO POLE) (SLOT DIPOLE)	 DITTO
2.0 AZIMUTH	2.1 MECHANICAL		
	2.1.1 MOTOR DRIVE	ALL	 FRICTION
	2.2 ELECTRICAL	MOST	 BELT GEAR ETC
	2.2.1 PHASE SHIFT OR SWITCH		
	2.2.2 MATRIX SWITCHING	(BUTLER MATRIX TYPE)	 OR ETC

7.0 TRACKING METHODS

Three tracking methods are considered for this system: the magnetic compass, pseudo sequential lobing by monopulse, and tracking by the receivers automatic gain control maximum voltage.

7.1 Magnetic Compass

The magnetic compass uses a north pointing magnetic compass to align the antenna beam position to magnetic north. R_1 is used to position the antenna to the maximum AGC voltage on installation (see Figure 7.1-1). As the automobile moves, travels around corners, etc., the difference between the compass potentiometer voltage and the voltage R_1 turns the antenna until the proper angular position is reached. The voltage across the servo amplifier then becomes zero. Since the azimuth beamwidth of the antenna is large, accuracy is not critical. The tracking rates were estimated from a car turning rate. The estimated tracking rat. is 50 degrees/sec and an acceleration of 20 degrees/sec/sec allows the antenna to maintain track at all times. Accuracy of the magnetic north seeker and its damping ratios is shown in Figure 7.1-2. The magnetic declination contours are shown in Figure 7.1-3. As can be seen, the required compensation for the magnetic declination is a slowly varying angle over large geographical distances. The receiver could be instrumented with a warning system that instructs the operator to adjust the antenna pointing, using R_1, until the AGC level is within normal voltage range. The magnetic compasses are expensive; approximate cost is $250. However, it is believed that less accurate magnetic compasses may be obtained at a lower cost.

7.2 Pseudo Sequential Lobing

The pseudo sequential lobing method is shown in Figure 7.2-1. The array has sum and difference outputs. A hybrid is used to develop the sum and difference pattern. A portion of the difference signal is injected into the sum channel by means of a coupler. The phase of the injected signal is injected sequentially in phase and out of phase, producing a sequentially switched beam position as shown in Figure 7.2-2. The signal is synchronously detected and the switching demodulated to develop right- and left-turn commands which are fed into the servo amplifier. The system is a closed-loop system which provides good close tracking at all times. By adding rate memory, the

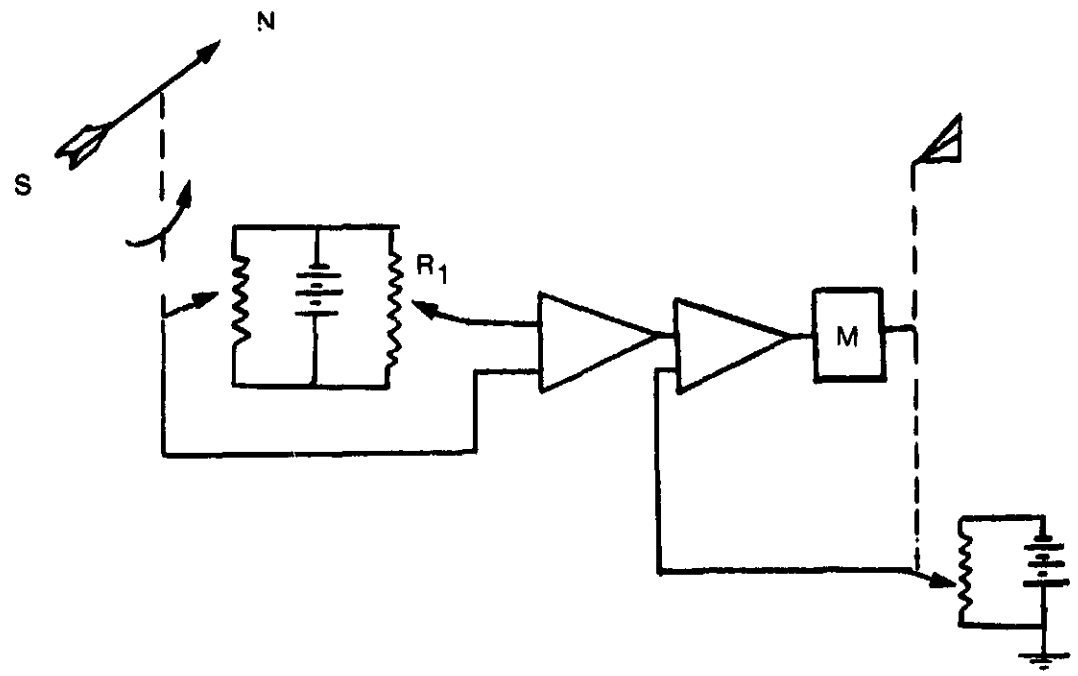


FIGURE 7.1-1. MAGNETIC NORTH SEEKERS SERVO SYSTEM

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NS04-0701-1

Fast response North Seeker® continuously registers magnetic north to accuracy of ∓5°. Only power requirement is for potentiometer excitation. Fluid filled. Pitch and roll freedom up to ∓40°. Adjustable ring compensator optional for operation in areas of distorted fields.

SPECIFICATIONS

RANGE

Azimuth	Continuous CW or CCW
Pitch and roll tolerance	∓30° maximum
Output	Potentiometer
Resistance	10,000 ohms ∓10%
Electrical travel	356° ∓2°
Power dissipation	0.5 watt
Accuracy	Within ∓8° with reference to earth's local magnetic field under static conditions or ∓3° with light inst. vib. or scorsby motion

ENVIRONMENTAL

Temperature	+32° F to +165° F
Vibration	At 5 G, 20 to 500 Hz
Shock	20 G (10 MS)

MECHANICAL

Weight	2.0 lbs. maximum



NS06-0102-2

Operates on less than ¼ watt from 12 VDC power supply. Accurate to within a 3° reference to magnetic north. Accommodates pitch and roll angles to 45°. Output is provided by precision, low torque potentiometer driven by magnetic compass. Sine and cosine potentiometers also available for direct azimuth readings.

SPECIFICATIONS

RANGE

Azimuth	360° mechanical, 355° ∓3° electrical
Pitch & roll clearance	up to ∓45°
Input voltage	10 to 30 VDC
Output	Potentiometer 5K ohms ∓10%
Accuracy	∓3° with reference to earth's magnetic field
Damping	Viscose 0.4 to 0.7 of critical

ENVIRONMENTAL

Temperature	+20° F to +120° F
Sealing	Hermetic
Vibration	5 G's to 20 to 500 Hz
Shock	20 G's (10 MS)

MECHANICAL

Weight	Less than 2 pounds



NS13-0101-1

A flux gate servo-type North Seeker® Sensing element is a standard flux gate coil suspended on a universal pivot. Provides accurate azimuth information with pitch and roll angles up to 45°. Output can be either synchro or potentiometer. Accuracy is within 2°. Suitable for buoys, boats, and borehole survey equipment. Used in offshore drilling. Input power required to internal DC inverter 24 to 30 VDC, current 0.130 amp.

SPECIFICATIONS

Azimuth	360°
Pitch & Roll	∓45°
Pickoff resistance	5,000 ohms ∓10%
Range	358° ∓ 1°
Power Dissipation	0.5 watts maximum
Voltage input	24 to 30 VDC
Current	0.130 amp
Time to speed	2 minutes nominal
Heading accuracy	2° maximum
Insulation resistance	20 megohms

ENVIRONMENTAL SPECIFICATIONS

Tenperature	-25° F to 140° F
Altitude	-1,000 feet to +70,000 feet
Vibration	5 to 500 Hz, 0.036 inch D.A. or 5 G whichever is the limiting value
Shock	20G/10 milliseconds
Humidity	0-95% relative humidity at 90° F
Sealing	"O" ring sealed
Weight	1.6 pounds

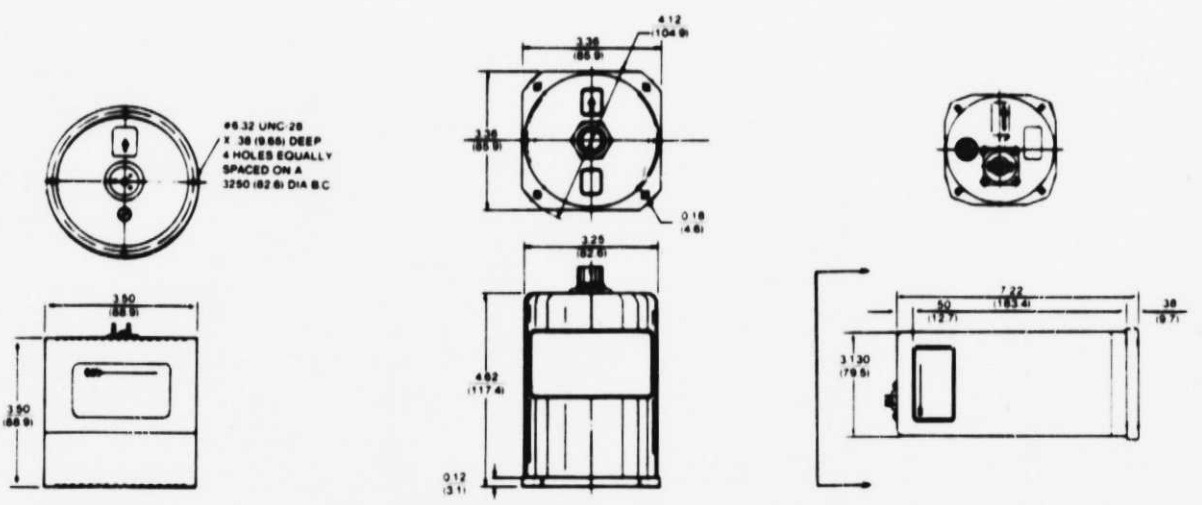


FIGURE 7.1-2. COMPASS DATA

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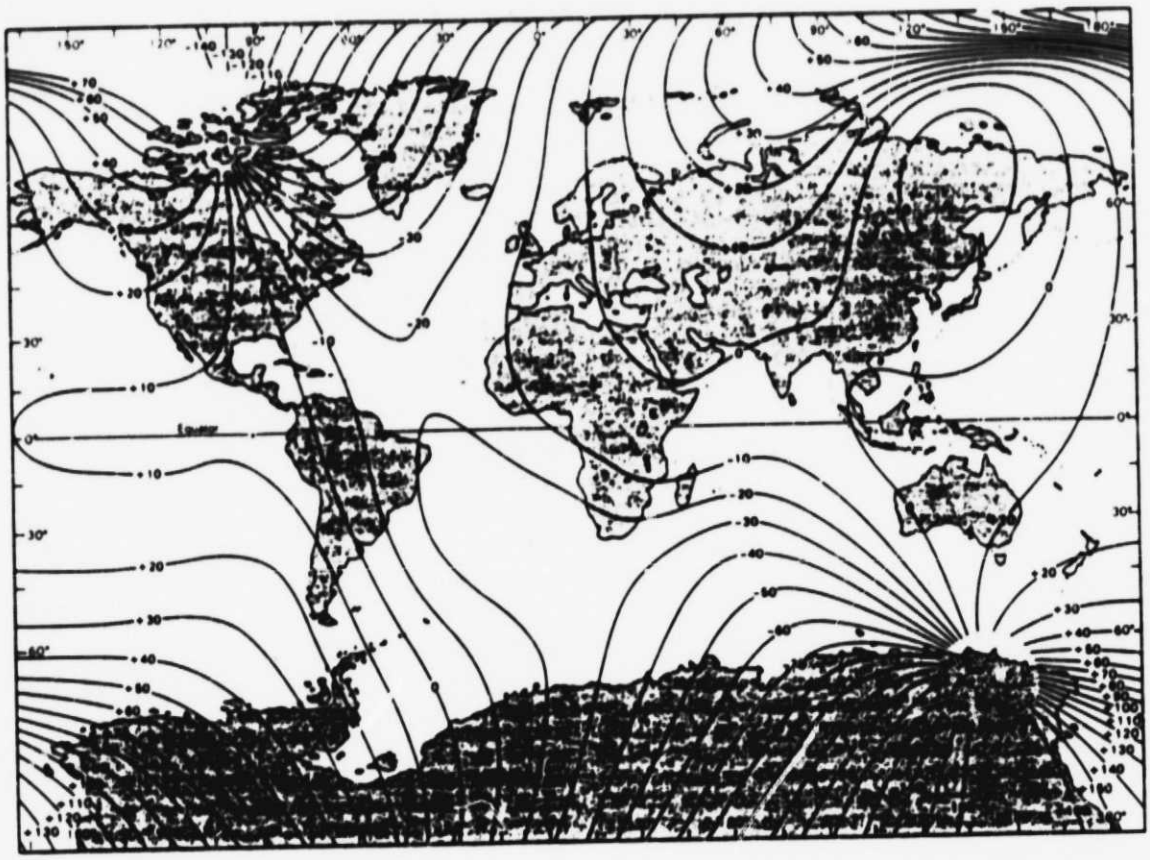


FIGURE 7.1-3. GEOMAGNETIC DECLINATION CONTOURS

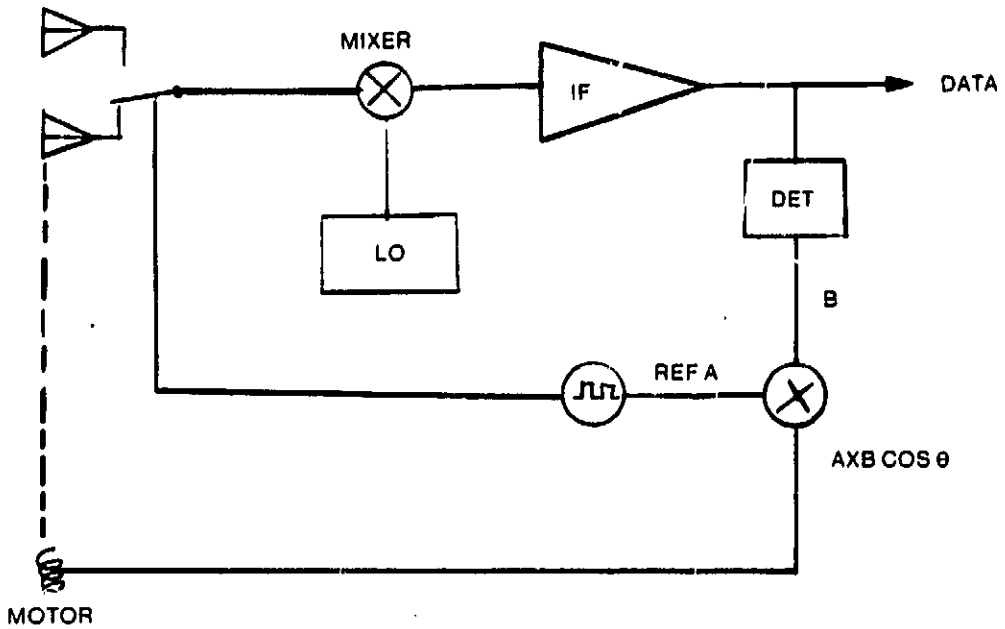


FIGURE 7.2-1. PSEUDO SEQUENTIAL LOBING SYSTEM BLOCK DIAGRAM

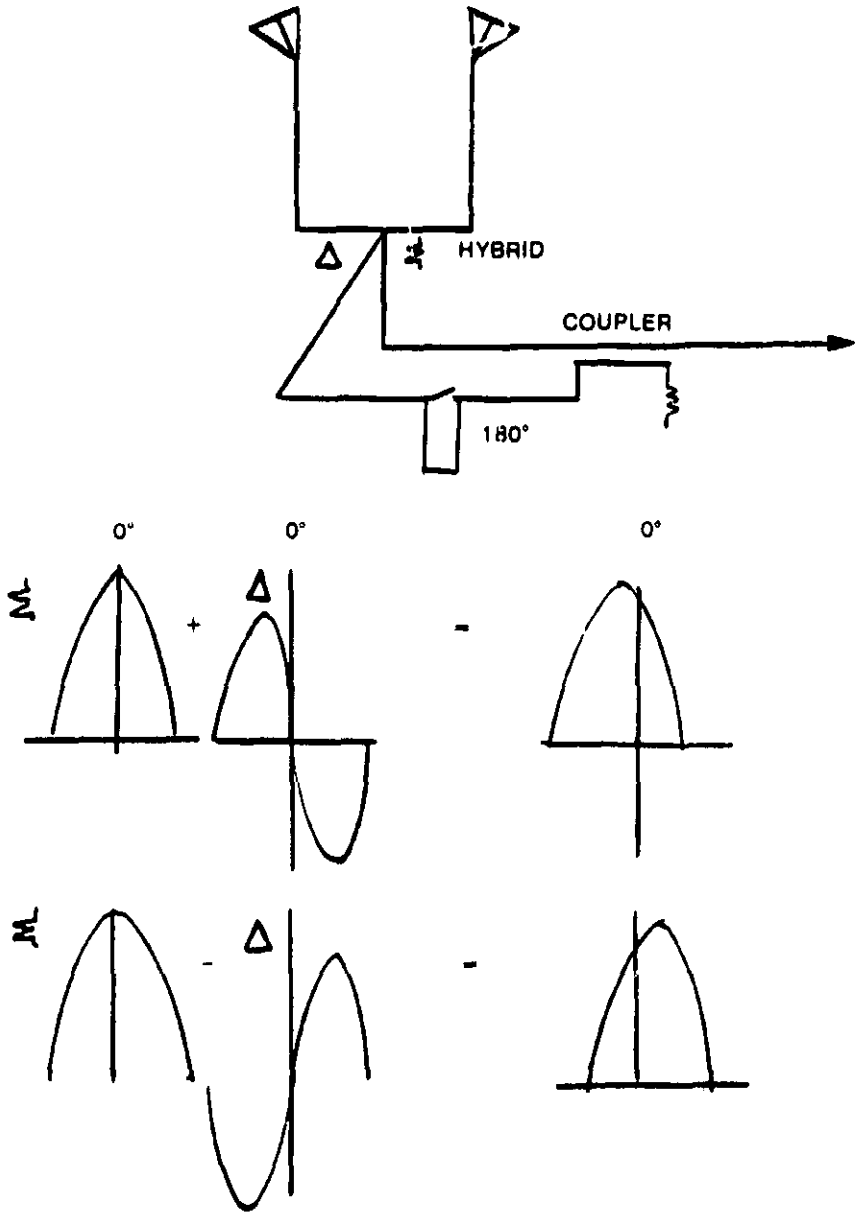


FIGURE 7.2-2. DEVELOPMENT OF SEQUENTIALLY LOBED BEAM

antenna will continue the turn at the same turn rate after the signal is lost. This turn rate can continue for several minutes if desired. Signal loss may occur because of overpasses, buildings, passing trucks, trees, etc. The RF circuit for this system can be fabricated in microstrip or stripline to produce low cost assembly.

The lobing switch signal can be sent up the rotary joint as shown in Figure 7.2-3. Acquisitions of the signal for automatic tracking is achieved by slewing the antenna in one direction if the AGC voltage is below a preset level. When the antenna reaches the point where the AGC reaches a higher preset lock-on level, the antenna servo loop is closed and the antenna will automatically track the satellite. Note that if the AGC lock-on level is set high enough, side lobes will not create false lockups. Figure 7.2-4 is a sketch of the motor drive for a typical antenna. Figure 7.2-5 is a block diagram of a typical servo system.

7.3 AGC Tracking

The AGC tracking method uses the AGC level to stop the antenna from searching. The antenna makes one turn, stores the maximum AGC level, starts another turn and stops at, or near, the maximum AGC level. As the car turns, the level will change. The system senses the change in level. When the level is reduced a preset amount, the antenna will be turned a small angular increment in one preset direction. If the AGC level increases, the antenna will again be advanced near the maximum AGC level. If the AGC is reduced with the first step, the antenna will then step backward until the AGC peak is reached.

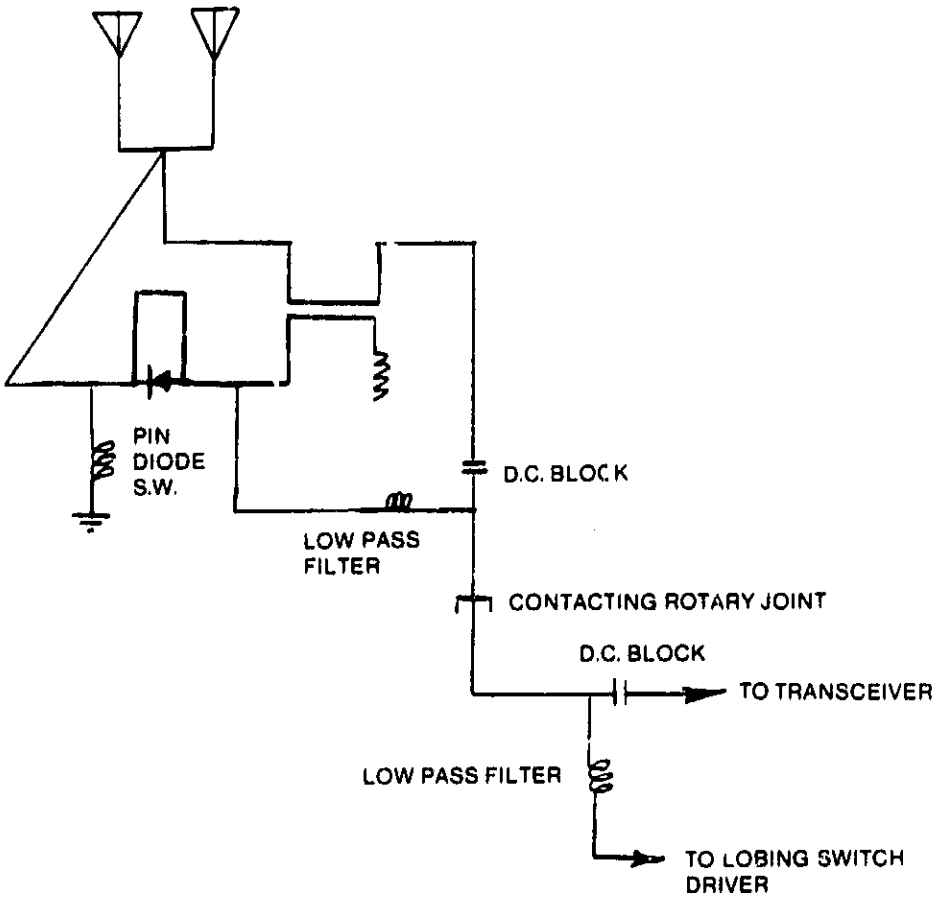


FIGURE 7.2-3. SWITCHING THROUGH ROTARY JOINT

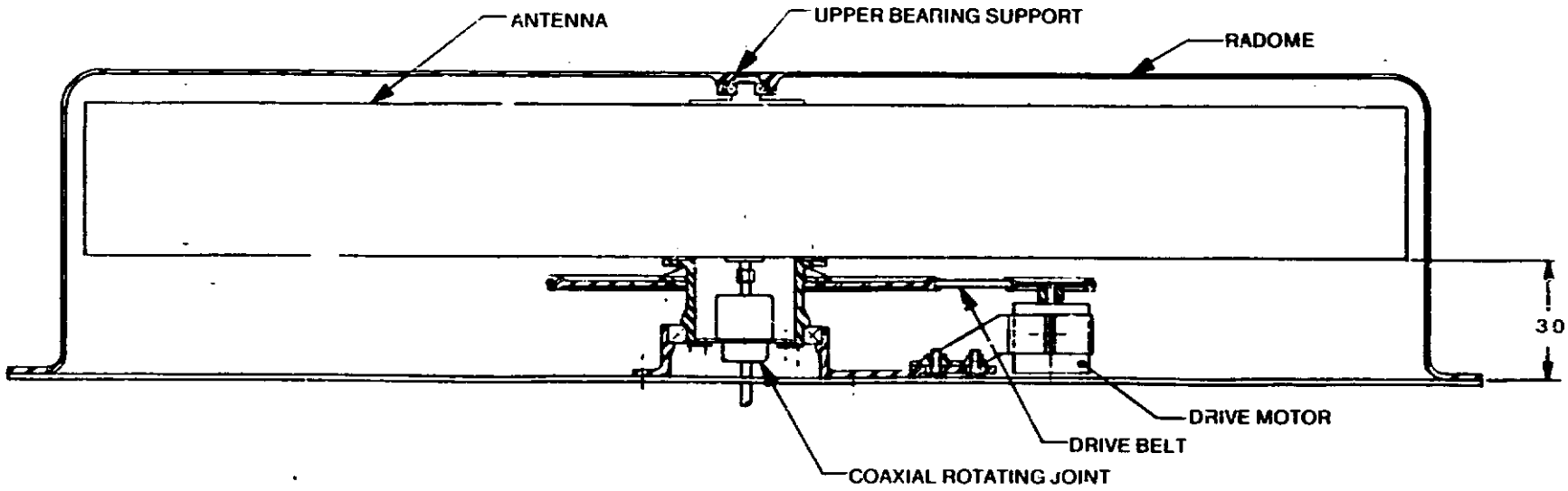


FIGURE 7.2-4. MOTOR DRIVE

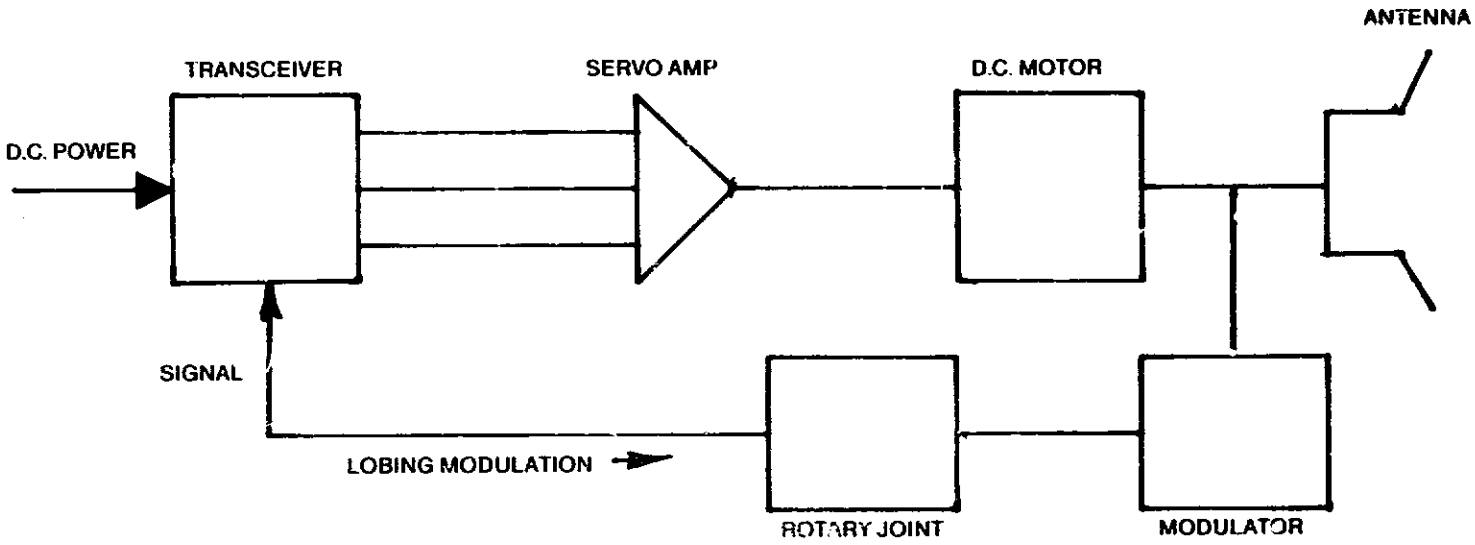


FIGURE 7.2-5. SERVO SYSTEM BLOCK DIAGRAM

8.0 NINE ANTENNA CONCEPTS SELECTED FOR COSTING

This section describes the nine antennas selected for costing. Two antennas, the crossed slot linear array and the ring array, were selected for detail study. They are discussed in detail in Section 10.

8.1 Linear Array

The linear array antenna is an array of radiating elements formed in a straight line. The array element may be any circularly polarized array element such as crossed dipoles, crossed slots, microstrip patch antennas, etc. The linear array element in this application was chosen to be cross slots (see Figure 8-1), although other array elements may prove more suitable for production, depending on the exact mechanical implementation of the antenna.

The ground plane affects the various elevation radiation patterns and is very important regardless of the element used. A crossed slot antenna was fabricated and a study made of its elevation radiation pattern performance as the antenna was tilted and elevated about the ground plane and corrugated surface. Figure 8.1-1 shows the microstrip feeding method and assembly of the antenna. The results of the elevation radiation pattern measurements are shown in Figure 8.1-2. The minimum gain over the coverage area which can be achieved with the antenna is tabulated in Table 8.1-1. Lower gains are achieved by reducing the number of azimuth elements. Table 8.1-2 is the radation pattern performance. The linear array is discussed in detail in Paragraph 10.2.

8.2 Helix Array

Figure 8.2-1 is a sketch of a two helix array. The helix is fed with a microstrip circuit with uniform amplitude for maximum gain. Elevation radiation patterns of the helix for various geometries and ground planes are shown in Figures 4.2-1 to 4.2-5. The optimum angle was found to be 30 degrees. The axial ratio under these circumstances was less than 5 dB. The gain characteristics are shown in Table 8.2-1. The pattern characteristics are tabulated in Table 8.2-2.

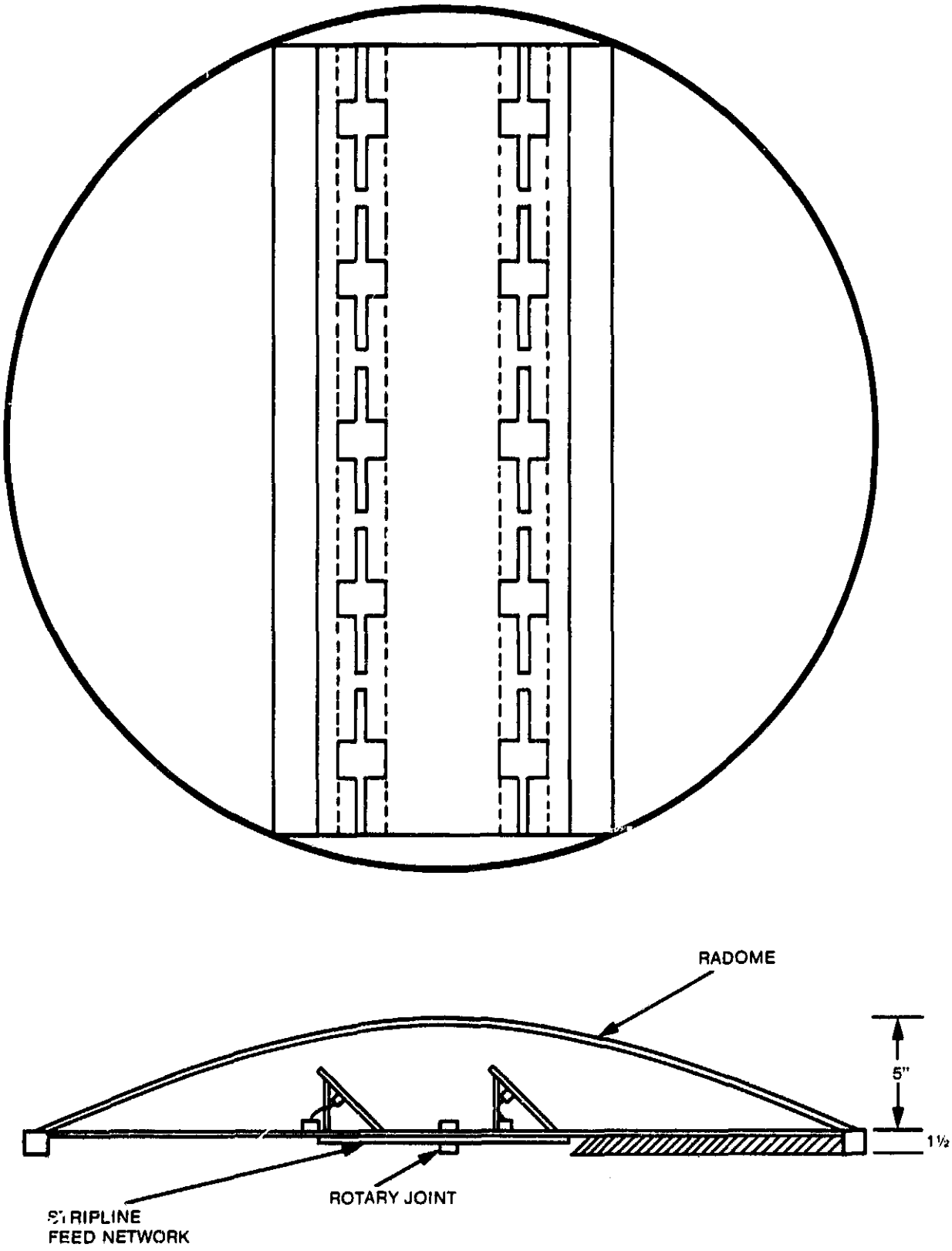


FIGURE 8-1. LINEAR ARRAY ANTENNA (12 DBCP GAIN)

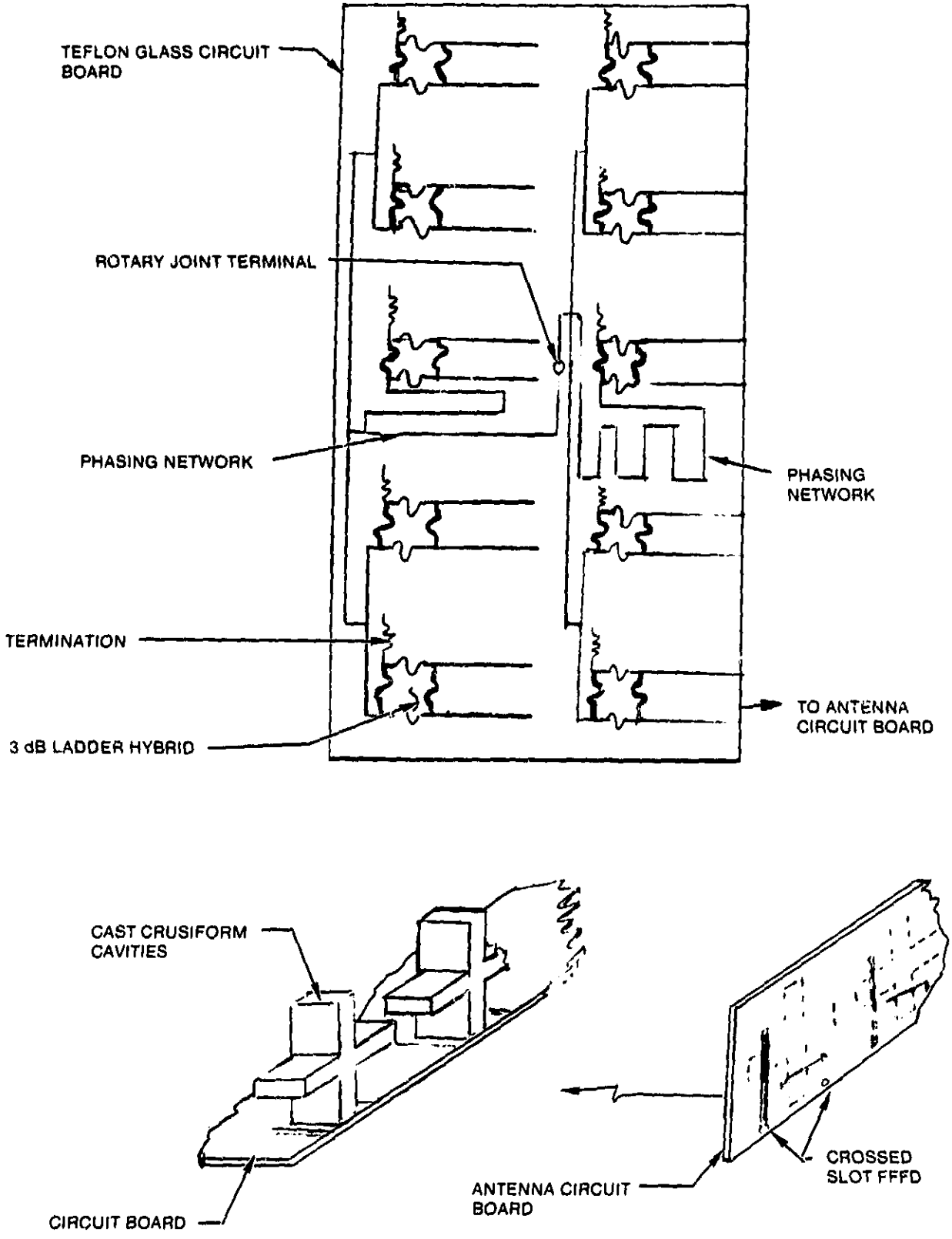


FIGURE 8.1-1. CIRCUIT BOARD AND ASSEMBLY

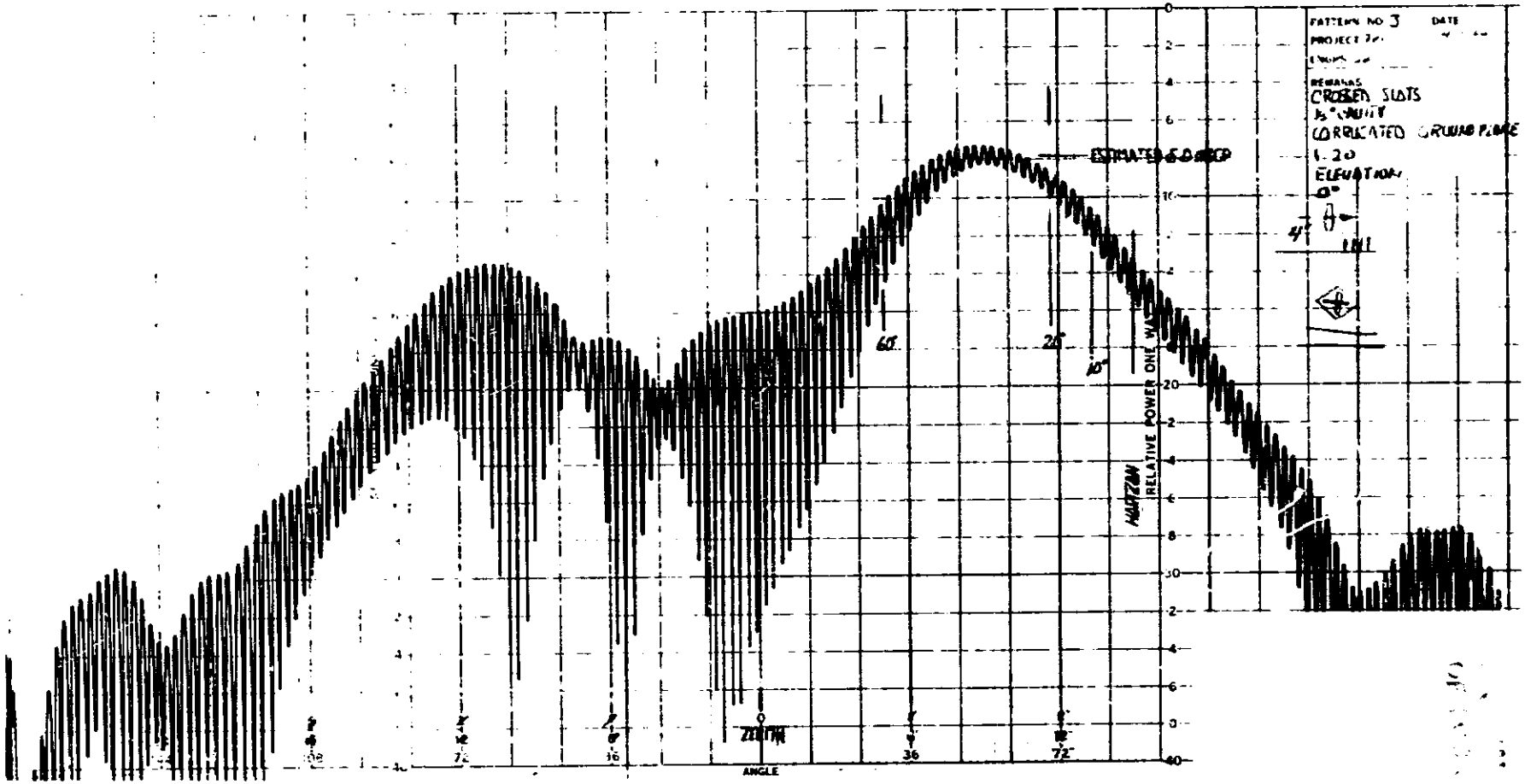


FIGURE 8.1-2. CROSSED SLOT ELEVATION PATTERN

TABLE 8.1-1
MINIMUM GAIN OVER COVERAGE AREA

GAIN CONUS

ARRAY 5 ISOTROPIC ELEMENTS @ λ/2 SPACING+	+7	dBCP
ELEMENT GAIN	+5	dB
ARRAY TWO ELEMENTS IN ELEVATION	+3.0	dB
I^2R LOSS - SWITCH & PCB	-0.5	dB
VSWR LOSS 1.8:1	-0.35	dB
ELEVATION COVERAGE LOSS AT 60 DEGREES	-1.1	dB
MONOPULSE CROSSOVER LOSS	-1.0	dB
	+12.05	dB

GAIN ALASKA

ARRAY 5 ISOTROPIC ELEMENTS @ λ/2 SPACING	+7	dBCP
ELEMENT GAIN	+5	dB
ARRAY TWO ELEMENTS IN ELEVATION	+3	dB
I^2R LOSS	-0.5	dB
VSWR LOSS	-0.35	dB
ELEVATION COVERAGE LOSS AT 10 DEGREES	-4	dB
MONOPULSE CROSSOVER LOSS	-0.5	dB
	9.55	dB

TABLE 8.1-2
ANTENNA PATTERN PERFORMANCE

AZIMUTH BEAMWIDTH - 3 dB	20
ELEVATION BEAMWIDTH - 3 dB	28
AXIAL RATIO - 3.5 dB	3.5 dB
PATTERN FALL-OFF 20 to 5 degrees	2 dB
PATTERN FALL-OFF 10 to 0 degrees	4.5 dB

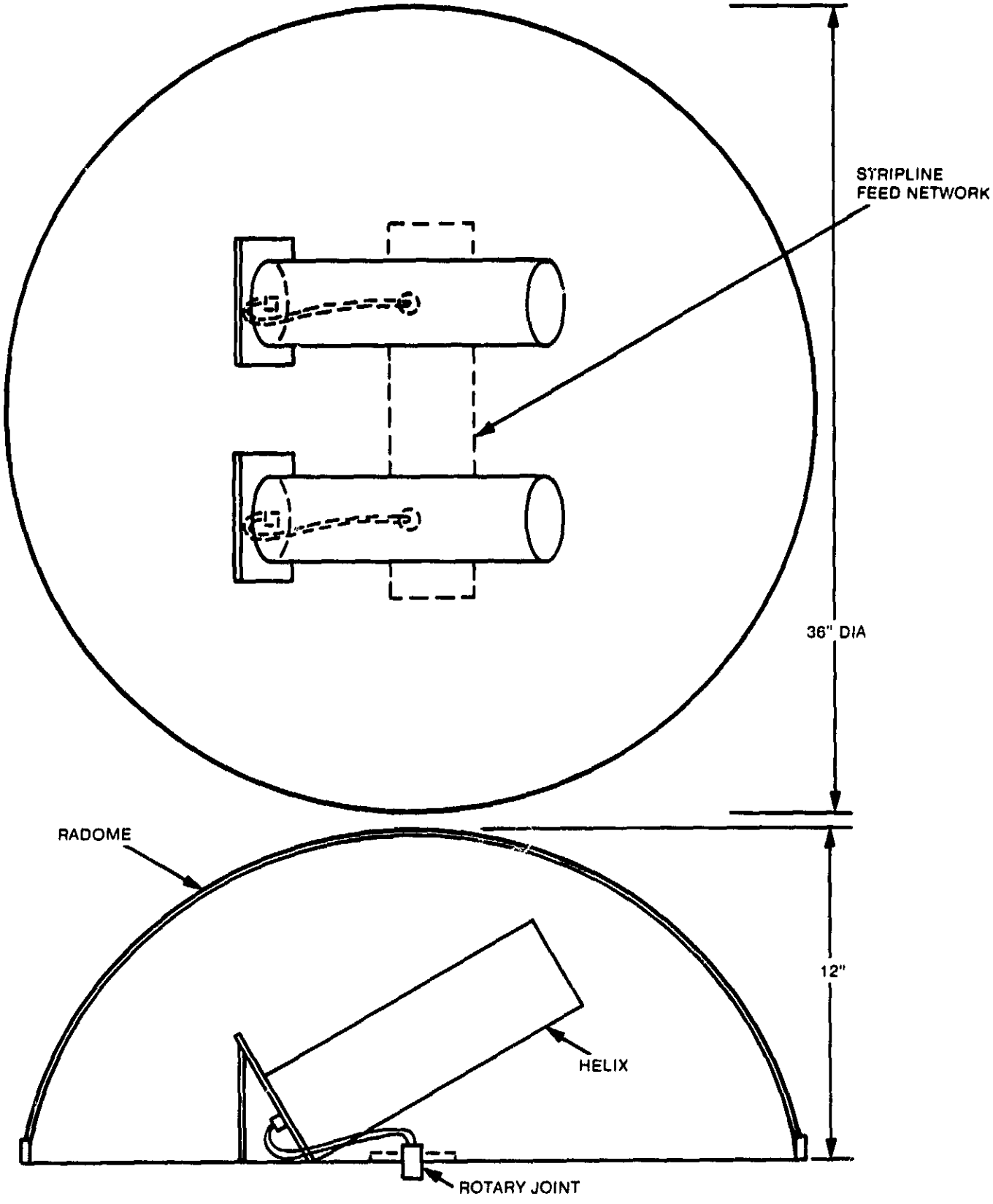


FIGURE 8.2-1. HELICAL ANTENNA

TABLE 8.2-1
HELIX GAIN CHARACTERISTICS

FIVE TURN HELIX - 2 ELEMENT AZIMUTH ARRAY; CONUS OR ALASKA

ONE HELIX GAIN	4.3 dBcp
TWO ELEMENT AZIMUTH ARRAY	3.0 dB
I^2R LOSS	-0.2 dB
MISMATCH LOSS, 1.5:1 VSWR	-0.2 dB
MONOPULSE CROSSOVER LOSS	-0.5 dB
	6.4 dB

EIGHT TURN HELIX - 2 ELEMENT AZIMUTH ARRAY CONUS OR ALASKA

ONE HELIX GAIN	6.4 dBcp
TWO ELEMENT AZIMUTH ARRAY	3.0 dB
I^2R loss	-0.2 dB
MISMATCH LOSS 1.5:1 VSWR	-0.2 dB
MONOPULSE CROSS OVER LOSS	-0.2 dB
	8.5 dBcp

EIGHT TURN HELIX - 4 ELEMENT AZIMUTH ARRAY CONUS OR ALASKA

ONE HELIX GAIN	6.4 dBcp
FOUR ELEMENT AZIMUTH ARRAY	6. dB
I^2R	-0.2 dB
MISMATCH LOSS 1.5:1 VSWR	-0.2 dB
MONOPULSE CROSS OVER LOSS	-0.2 dB
	+11.5 dB dBcp

TABLE 8.2-2
RADIATION PATTERN CHARACTERISTICS

	FIVE TURN TWO ELEMENT	EIGHT TURN TWO ELEMENT	EIGHT TURN FOUR ELEMENT
AZIMUTH BEAM WIDTH	40°	31°	20°
ELEVATION BEAM WIDTH	56°	42°	42°
FALL OFF TO 5°	3 dB	3 dB	3 dB
FALL OFF TO 0°	3 dB	5 dB	5 dB
AXIAL RATIO	5 dB	5 dB	5 dB

8.3 Parabolic Antenna

Figure 8.3-1 is a sketch of the parabolic antenna. The antenna is fed with a crossed slot microstrip feed. The antenna is scanned in elevation for maximum AGC signal using a motor-driven jack screw. One scan is made by scanning the antenna upward. As the antenna passes through a maximum the antenna stops and then reverses itself until the maximum is reached. The characteristics of the antenna are tabulated in Tables 8.3-1 and 8.3-2 for the gains and radiation pattern performance. There were no empirical data taken with this antenna because its size is outside the desirable height. The gain levels may be met by increasing the antenna size as required.

8.4 Horn Antenna

Figures 8.4-1 and 8.4-2 show the horn array. Using two elements, the antenna has a gain of 6 dBcp; using four elements the gain in CONUS is 9 dBcp. The upper array of Figure 8.4-2 has a gain of 12 dBcp. It may be phased to optimize the elevation pattern coverage in two beam positions. A switch is used to phase the upper antenna with the lower antenna for changing beam position. Th switching circuit uses the rotary joint. If the antenna is being sequentially lobed by a pulse signal through the rotary joint a square wave signal can be sent through the rotary joint. The positive portion, for instance, can be used to modulate the signal. The negative portion can be used to switch the phase shifter. If the negative portion is averaged into a negative voltage, the absence of the negative voltage would switch the circuit to its normal position. Figure 8.4-3 is a circuit for switching.

8.5 Patch Array

The 1 x 5 patch array is similar in performance to the crossed slot array. Figure 8.5-1 shows a sketch of the patch array. The elevation pattern of the antenna without a ground plane is shown in Figure 8.5-2. The pattern of the antenna mounted on the ground plane will be similar to the crossed slot but will be narrower because the patch is an array of two elements.

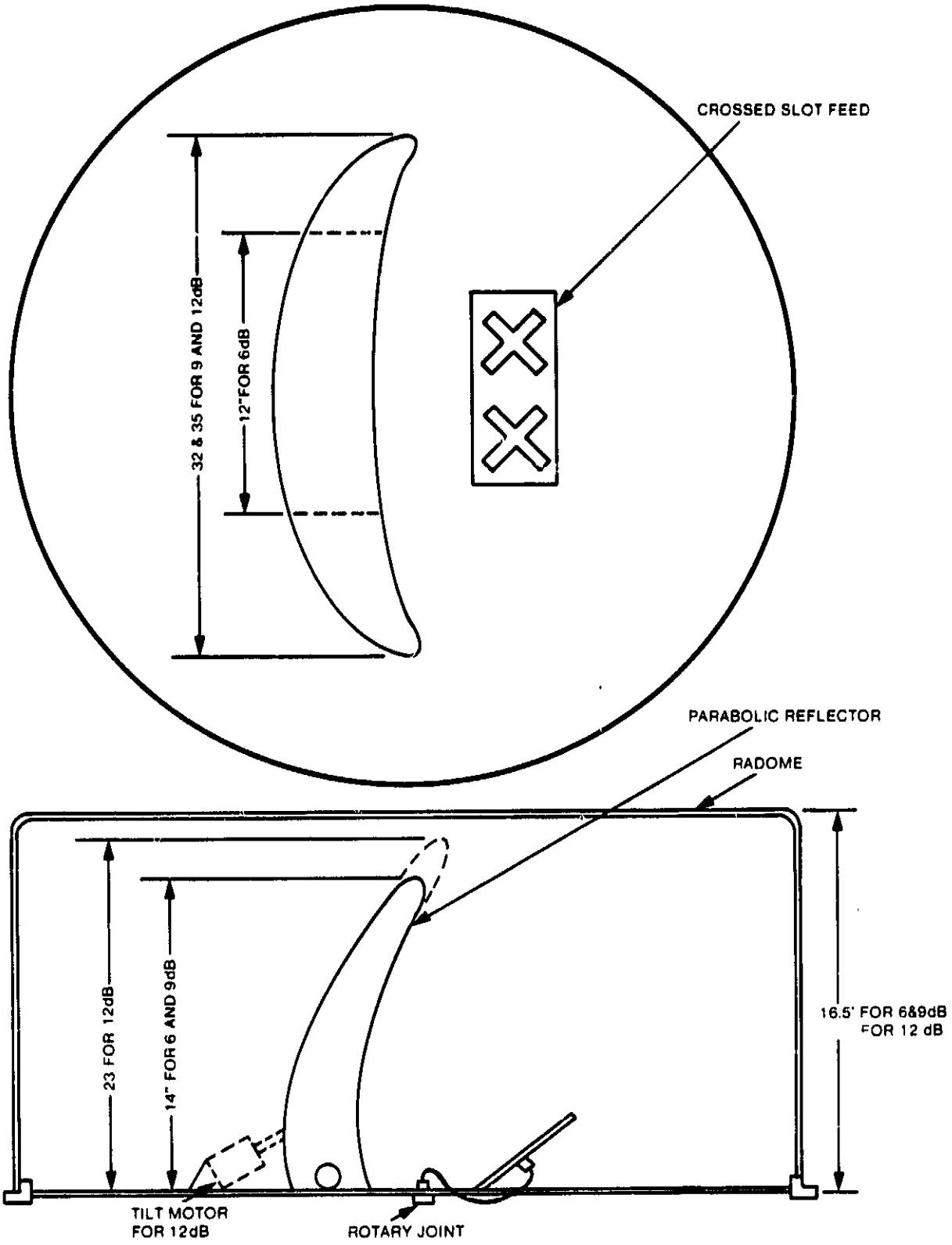


FIGURE 8.3-1. PARABOLIC ANTENNA

TABLE 8.3-1

PARABOLIC ANTENNA GAIN

ANTENNA GAIN -6 dBcp	
HEIGHT	14 inches
WIDTH	16 INCHES
AREA, 50% EFFICIENCY	230 IN SQ
GAIN	+8.9 dBcp
I^2R LOSS	-0.1 dB
MISMATCH LOSS 1:5:1 VSWR	-0.2 dB
ELEVATION COVERAGE LOSS	-1.5 dB
AZIMUTH MONOPULSE CROSSOVER LOSS	-1.0 dB
	+6.1 dBcp
ANTENNA GAIN -9 dBcp	
HEIGHT	14 inches
WIDTH	32 INCHES
AREA, 50% EFFICIENCY	460 IN SQ
GAIN	+11.9 dBCP
I^2R LOSS	-0.1 dB
MISMATCH LOSS 1:5:1 VSWR	-0.2 dB
ELEVATION COVERAGE LOSS	-[illegible] dB
AZIMUTH MONOPULSE CROSSOVER LOSS	-1.0 dB
	+9.1 dBcp
ANTENNA GAIN 12 dBcp	
HEIGHT	23 INCH
WIDTH	35 INCH
AREA, 50% EFFICIENCY	819
GAIN	+14.4 dBcp
I^2R LOSS	-0.1 dB
MISMATCH LOSS 1:5:1 VSWR	-0.2 dB
ELEVATION COVERAGE LOSS	-1.5 dB
AZIMUTH MONOPULSE CROSSOVER LOSS	-0.5 dB
	+12.1 dBcp

TABLE 8.3-2
PARABOLIC ANTENNA RADATION
PATTERN CHARACTERISTICS

	GAINS		
	6 dB	9 dB	12 dBcp
AZIMUTH BEAM WIDTH	60^{o}	30^{o}	26^{o}
ELEVATION BEAMWIDTH	70^{o}	70^{o}	30^{o}
PATTERN COVERAGE	3 dB	3 dB	3 dB
PATTERN COVERAGE	4 dB	4 dB	4 dB
AXIAL RATIO	3 dB	3 dB	3 dB

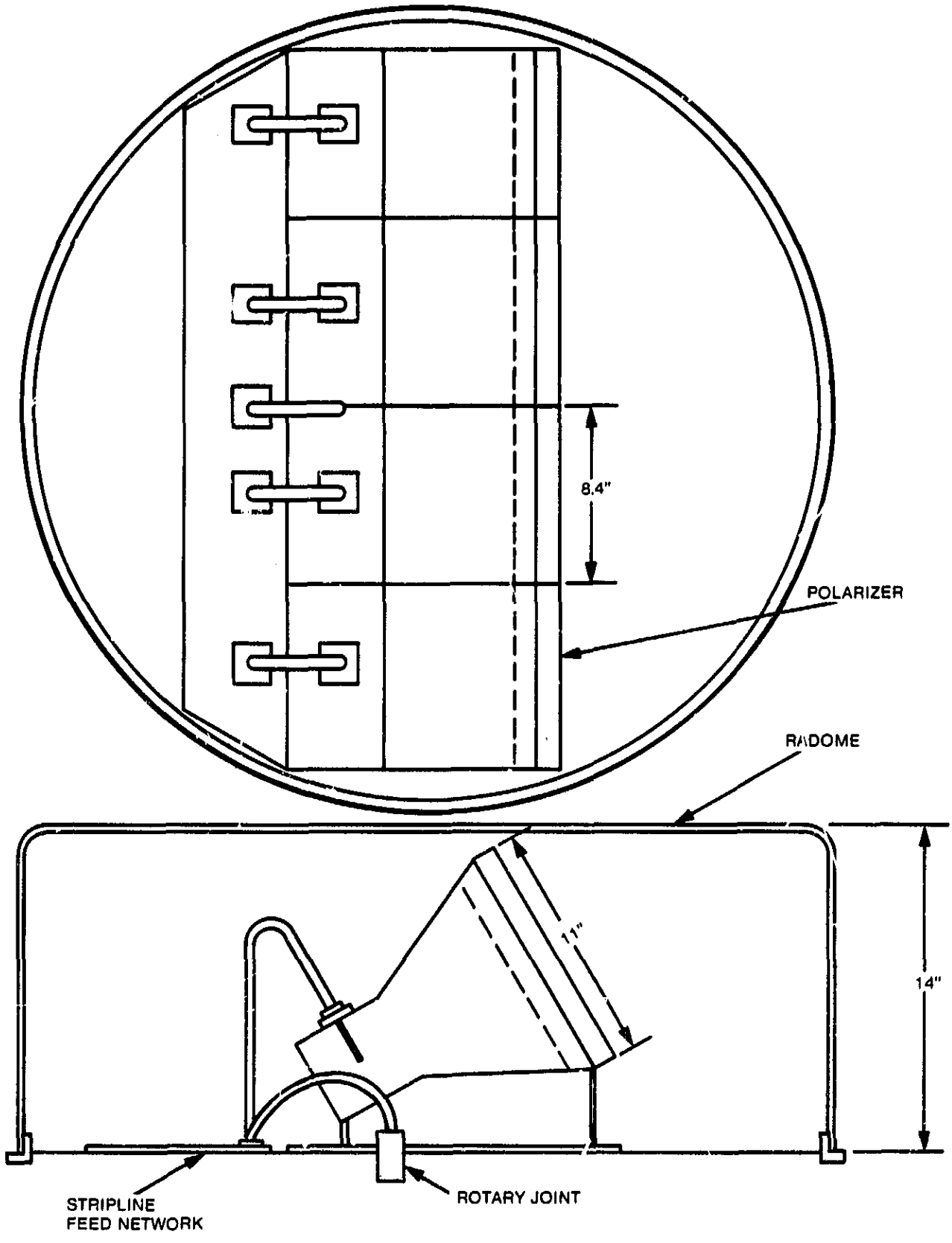


FIGURE 8.4-1. GAIN HORN ANTENNA -9 dBcp GAIN

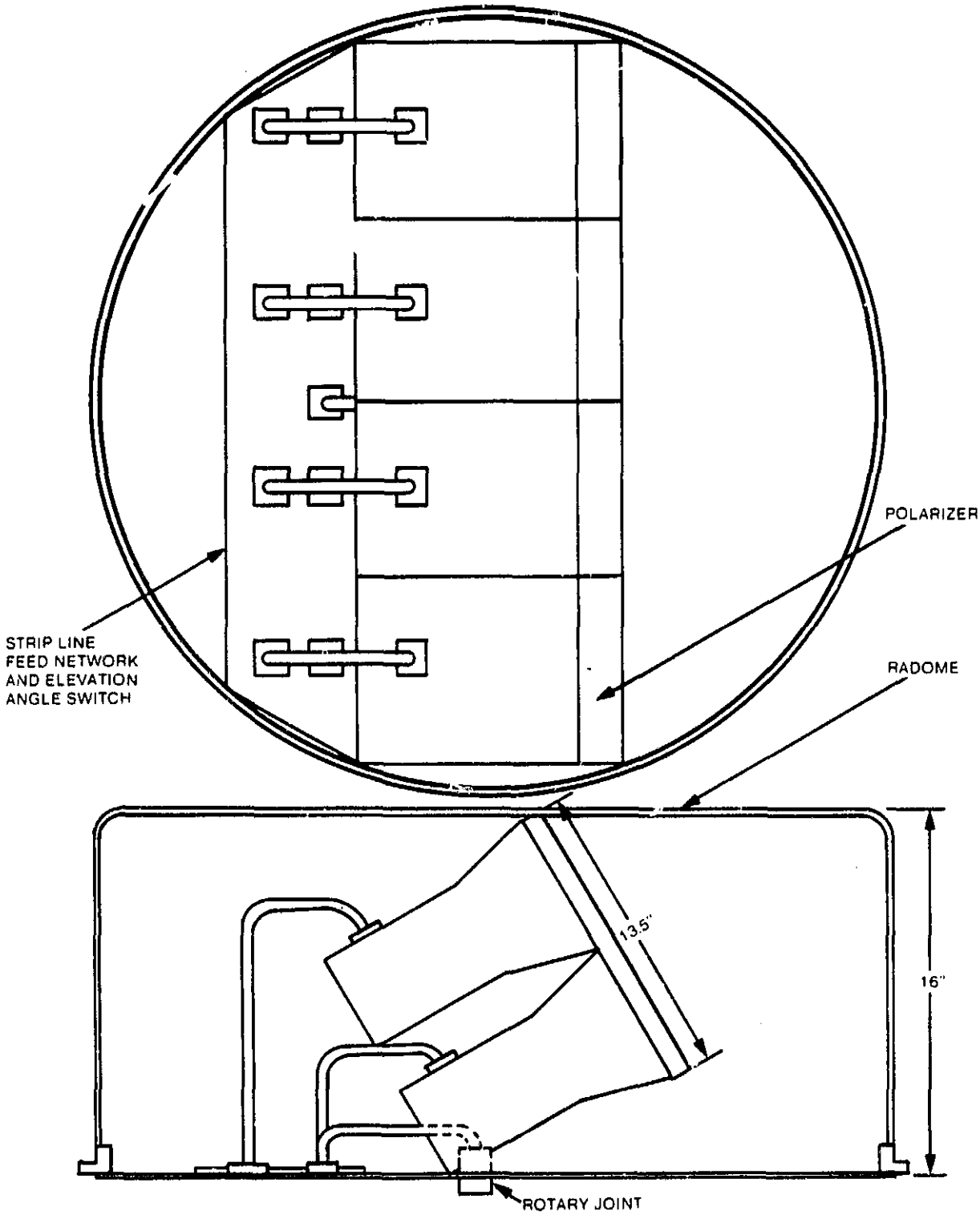


FIGURE 8.4-2. GAIN HORN ANTENNA -12 dBcp GAIN

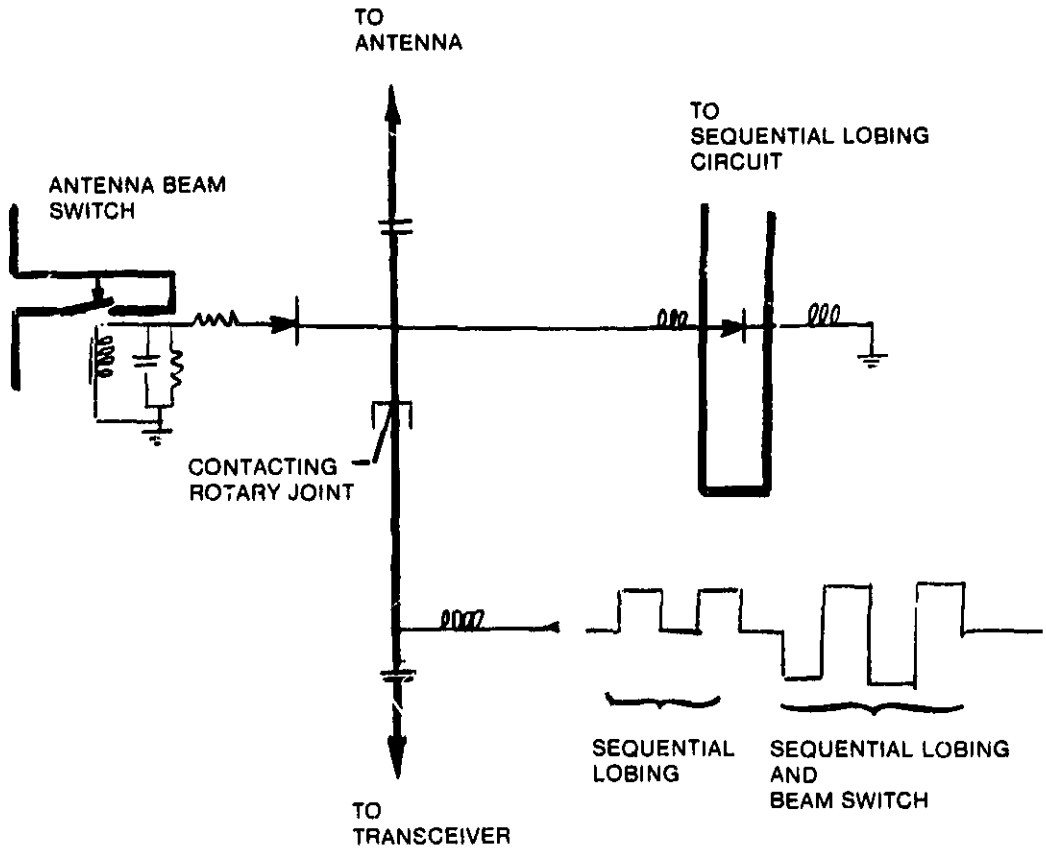
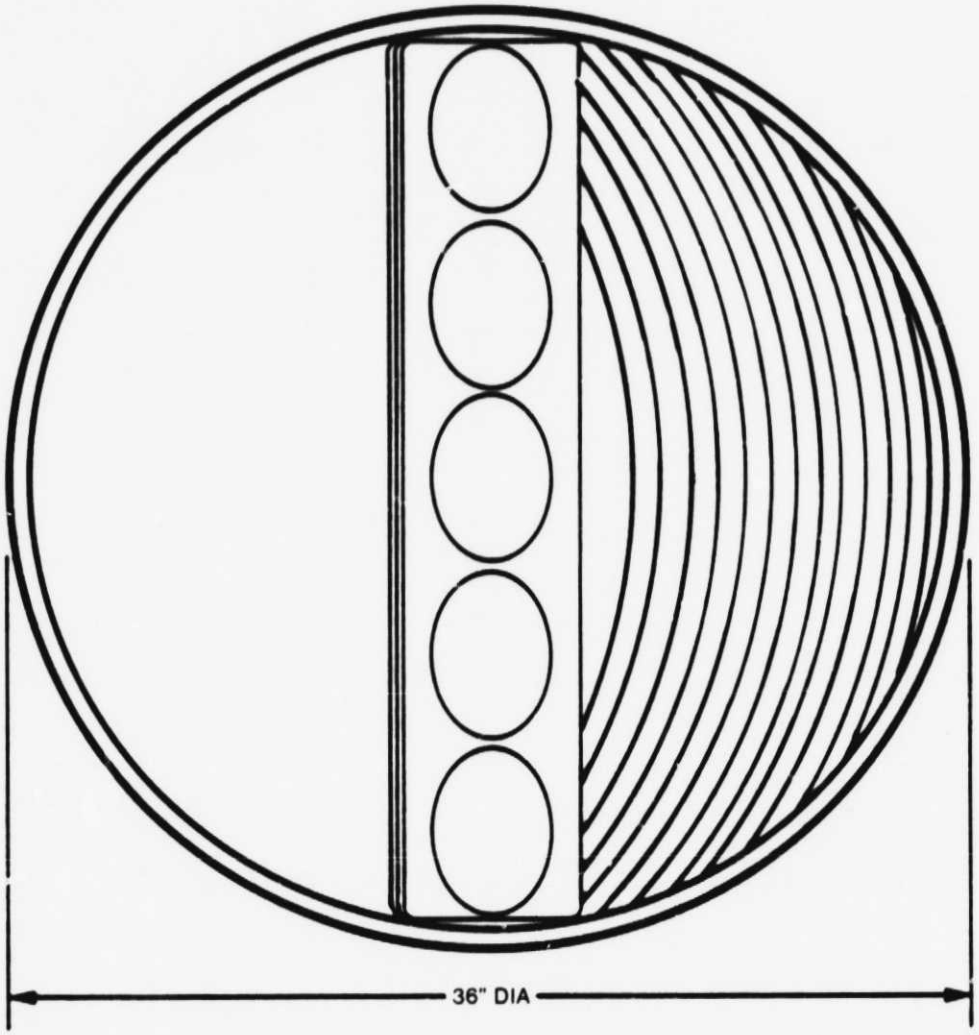


FIGURE 8.4-3. LOBE SWITCHING AND BEAM SWITCHING



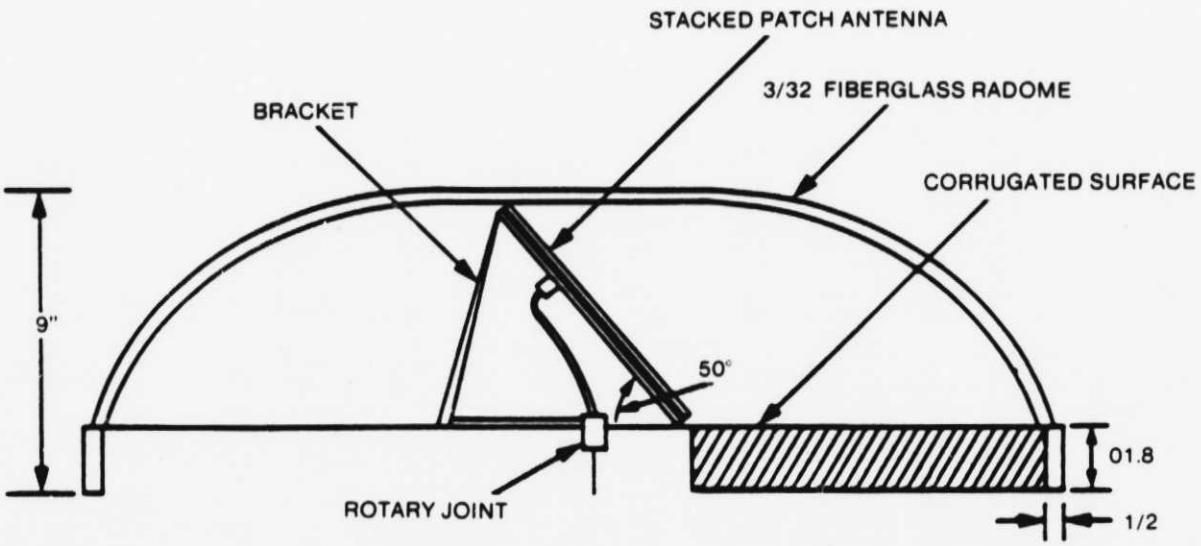


FIGURE 8.5-1. PATCH ANTENNA

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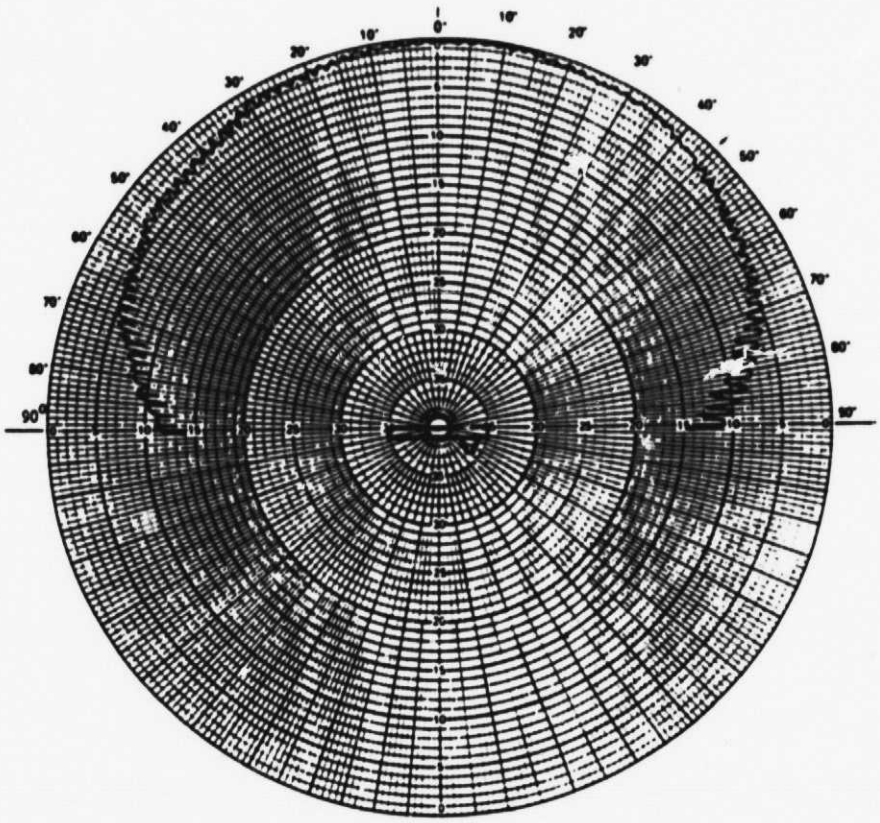


FIGURE 8.5-2. RADIATION PATTERN OF PATCH WITH ROTATING LINEAR

8.6 Corner Reflector

The corner reflector is discussed in paragraphs 4.1.

8.7 Monopole Array

The monopole array is shown in Figure 8.7-1. The array of two, four, and five monopole elements will give a gain of 6, 9, and 12 dBcp respectively. The antenna requires a polarization grating for circular polarization and corrugated surface to shape the beam. The grating makes the antenna large. The corrugated surface will cause the pattern to drop off rapidly toward the horizon. The performance is shown in Table 8.7-1.

8.8 Ring Array

The ring array was selected for further study and is presented in detail in Section 10.

8.9 Conformal Array

The conformal array has its elements on a flat surface as shown in Figure 8.9-1. The elements are arranged in a cruciform and spaced approximately one-half wavelength apart. Although other geometries may be used to reduce the number of elements, this was not pursued since the antenna cost is very high. The greatest cost is the phase shifters. Each element requires a $200 phase shifter. Table 8.9-1 is a tabulation of this gain.

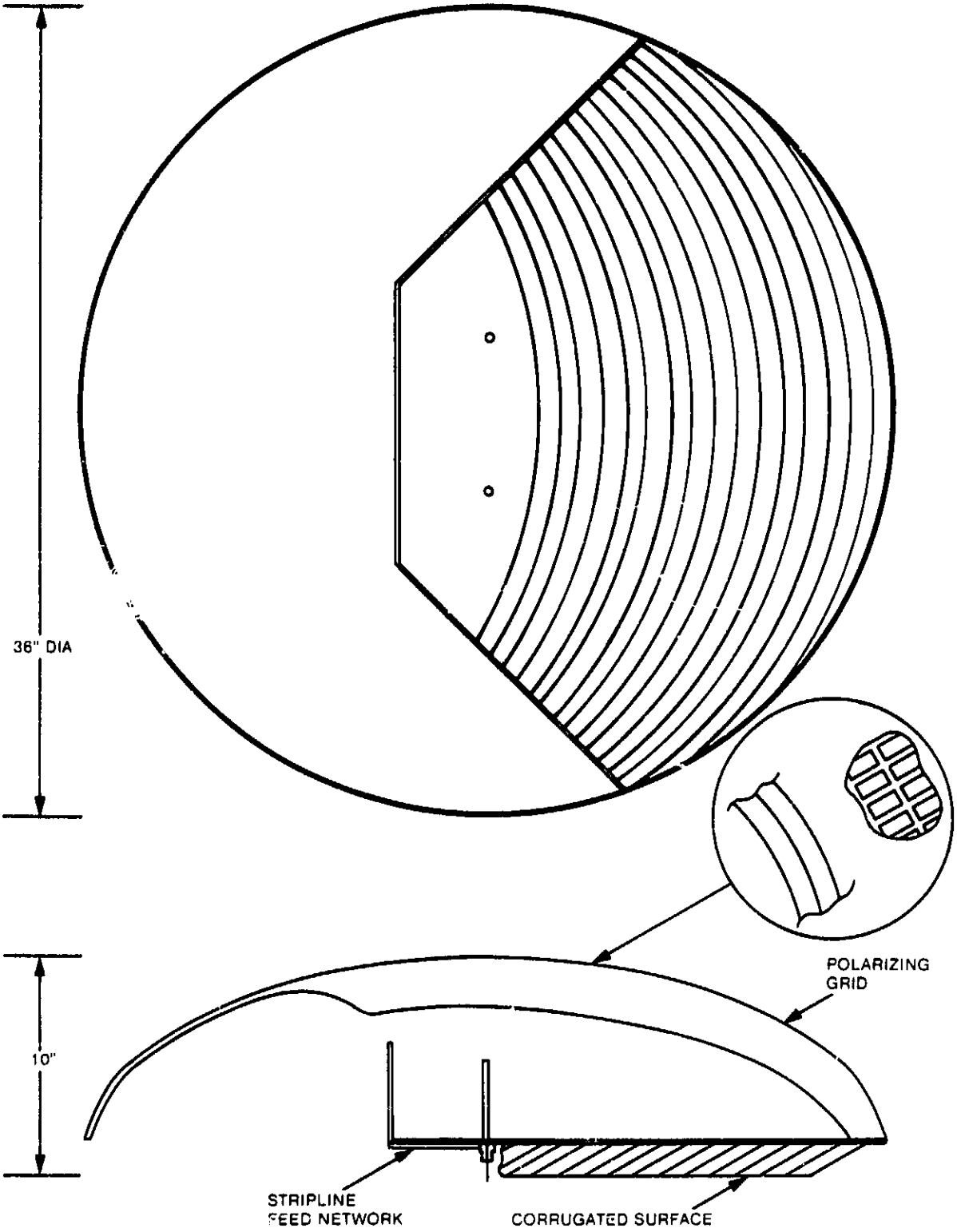


FIGURE 8.7-1. MONOPOLE TWO ELEMENT ARRAY

TABLE 8.7-1

MONOPULE ARRAY PERFORMANCE CHARACTERISTICS

	GAIN CONUS	GAIN ALASKA
DIRECTIVITY 5 ELEMENTS	8 dB	8 dB
ELEMENT GAIN AT REQUIRED ANGLES	2.5 dBcp	0.5 dBcp
VSWR LOSS 1.8:1 VSWR	-0.35 dB	-0.35 dB
I^2R LOSS	-0.20 dB	-0.20 dB
CROSSOVER LOSS	0.50 dB	-0.50 dB
MONOPULSE POLARIZER LOSS	-0.50 dB	-0.50 dB
	9 dBcp	7 dBcp

AZIMUTH BEAMWIDTH -3 dB	20^o
ELEVATION BEAMWIDTH -3 dB	45^o
PATTERN ROLL OFF 5^c dB	5
PATTERN ROLL OFF 0^o dB	7

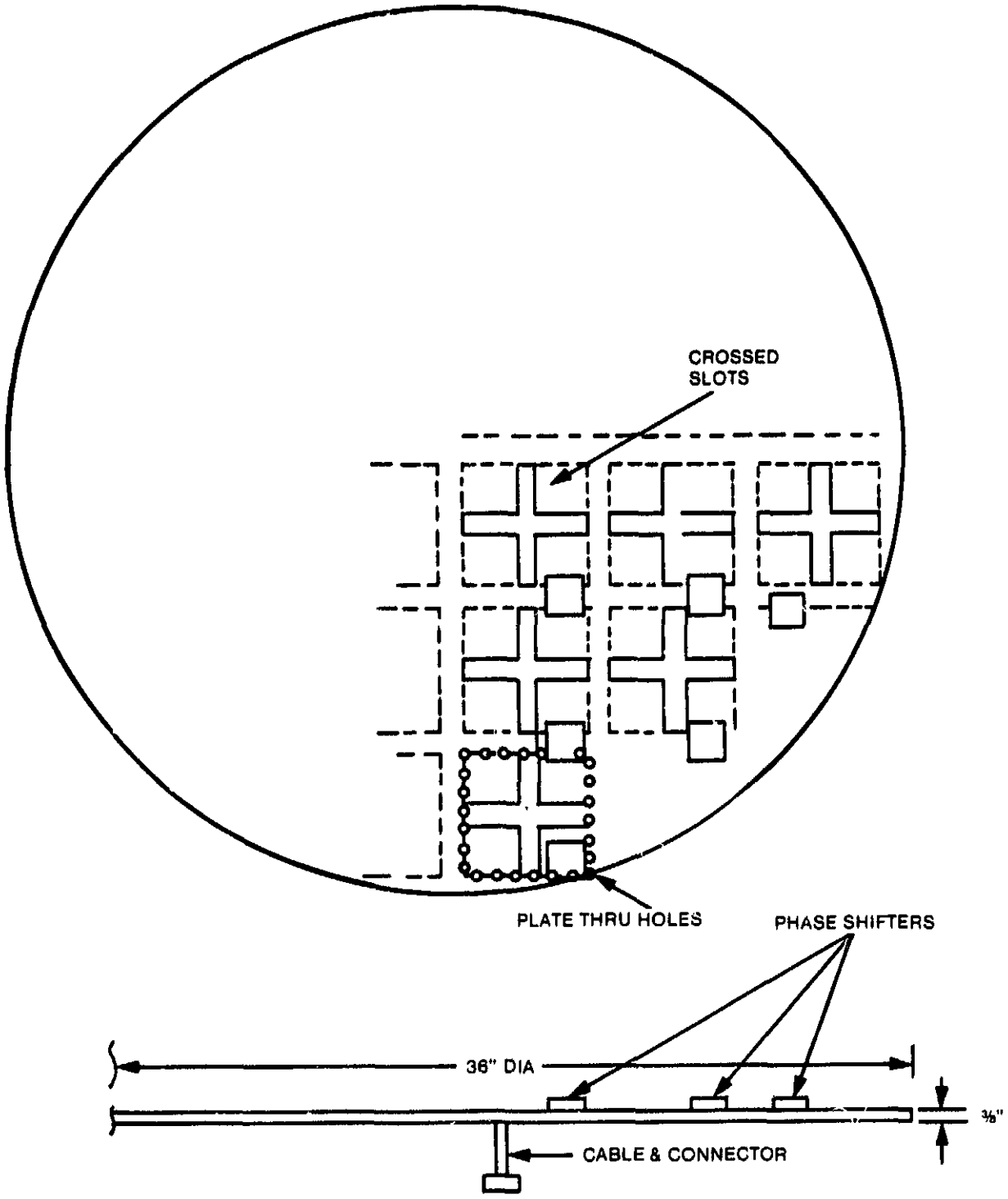


FIGURE 8.9-1. GAIN CONFORMAL ANTENNA 9 dBcp

TABLE 8.9-1

CONFORMAL ARRAY PERFORMANCE CHARACTERISTICS

	CONUS	ALASKA
DIRECTIVITY 24 ELEMENT ARRAY	14.5 dB	14.5 dB
GAIN-ELEMENT	5.3 dBcp	5.3 dBcp
SCAN LOSS TO 60 DEGREES	-3.0 dB	-3.0 dB
ELEVATION PATTERN COVERAGE LOSS	-4.0 dB	-6.6 dB
PHASE SHIFTER LOSS	-2.0 dB	-2.0 dB
i^2R AND MISSMATCH LOSS	-0.6 dB	-0.6 dB
AZ BEAM MONOPULSE CROSSOVER SCAN LOSS	-0.5 dB	-0.5 dB
	9.1 dBcp	7.1 dBcp

AZIMUTH BEAMWIDTH -3 dB	20°
ELEVATION BEAMWIDTH -3 dB	26°
PATTERN ROLL OFF -5° dB	2 dB
PATTERN ROLL OFF -0° dB	4 dB

9.0 TWO SATELLITE ISOLATION STUDY

9.1 Introduction

Part of this Experimental Mobile Satellite Program study must be directed to the problems associated with systems that use multiple satellites to complete telephone links throughout the region of service. The most significant of these problems is isolation. It has been established that the signal sent to the intended satellite must exceed the leakage of that signal to any nonparticipating satellite by 20 dB to ensure trouble free operation.

9.2 Look Angle Calculation

The literature[1] provides a graphical solution for the angular coordinates to any satellite in synchronous orbit from any location on earth. Following is a rigorous derivation of expressions which may be used to calculate more precise azimuth and elevation values.

Let the location of a satellite in orbit a distance R from the origin of a geocentric frame of reference (Figure 9-1) be represented by the vector $\bar{R}$ where:

$$\bar{R} = \begin{bmatrix} R_x \\ R_y \\ R_z \end{bmatrix} = \begin{bmatrix} R \cos \phi_s \cos \theta_s \\ R \sin \phi_s \cos \theta_s \\ R \sin \theta_s \end{bmatrix}$$

such that

ϕ_s = satellite longitude

θ_s = satellite latitude

R = 42166 km

The following rotations and translations are necessary to redefine the satellite referenced to an array located on the earth at a specific latitude and longitude.

[1] Vogel, Wolfhard; "Graph Points You Toward Any Synchronous Satellite", Microwave Journal, Oct. 1977

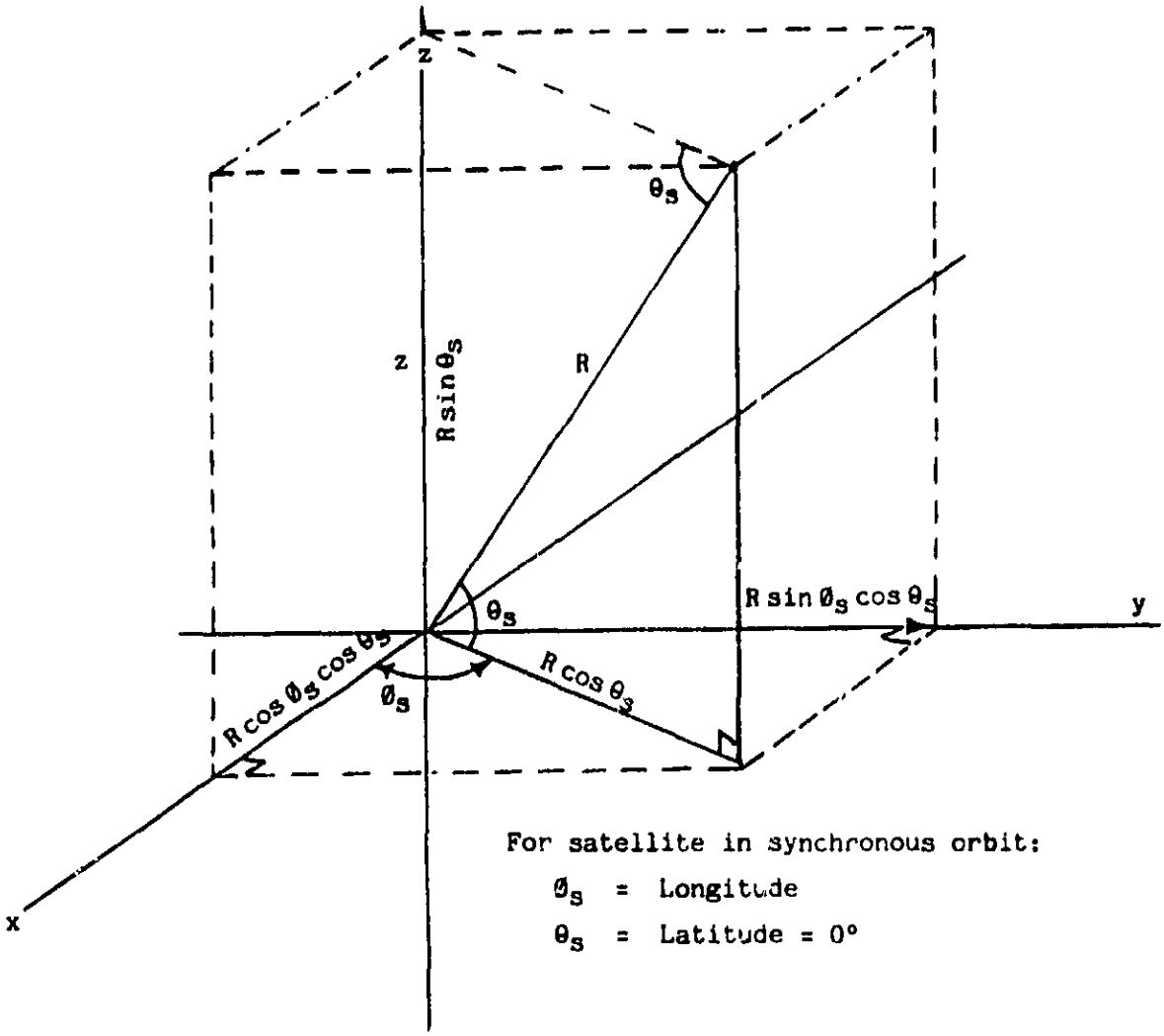


FIGURE 9-1

GEOCENTRIC FRAME OF REFERENCE

Z axis rotation of $\emptyset_e + 180$ is accomplished by multiplying the vector $\bar{R}$ by the direction cosine matrix C_z to obtain $\bar{R}'$.

$$C_z = \begin{bmatrix} -\cos \emptyset_e & -\sin \emptyset_e & 0 \\ +\sin \emptyset_e & -\cos \emptyset_e & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

where $\emptyset_e$ = earth station longitude.

$$\bar{R}' = \begin{bmatrix} R \cos \theta_s \cos (\Delta\emptyset) \\ R \cos \theta_s \sin (\Delta\emptyset) \\ R \sin \theta_s \end{bmatrix}$$

$\Delta\emptyset$ = satellite longitude - earth station longitude

Y axis rotation of $90 - \theta_e$ orients the Z axis towards the zenith at the location of the earth station. This is accomplished by multiplying $\bar{R}'$ by the direction cosine matrix C_y to obtain $\bar{R}''$.

$$C_y = \begin{bmatrix} \sin \theta_e & 0 & -\cos \theta_e \\ 0 & 1 & 0 \\ \cos \theta_e & 0 & \sin \theta_e \end{bmatrix}$$

where θ_e = earth station latitude

$$\bar{R}'' = \begin{bmatrix} R [\cos (\Delta\emptyset) \sin \theta_e \cos \theta_s - \sin \theta_s \cos \theta_e] \\ R [\cos \theta_s \sin (\Delta\theta)] \\ R [\cos (\Delta\emptyset) \cos \theta_e \cos \theta_s + \sin \theta_s \sin \theta_e] \end{bmatrix}$$

Z axis translation a distance, r, equal to the earth's radius places the new reference origin at the center of the array.

$$\bar{R}''' = \begin{bmatrix} R [\cos (\Delta\emptyset) \sin \theta_e \cos \theta_s - \sin \theta_s \cos \theta_e] \\ R [\cos \theta_s \sin (\Delta\emptyset)] \\ R [\cos (\Delta\emptyset) \cos \theta_e \cos \theta_s + \sin \theta_s \sin \theta_e] - r \end{bmatrix}$$

For satellites in synchronous orbit, $\theta_s = 0$, and $\bar{R}'''$ simplifies to:

$$\begin{bmatrix} R_x''' \\ R_y''' \\ R_z''' \end{bmatrix} = \begin{bmatrix} R \cos(\Delta\emptyset) \sin\theta_e \\ R \sin(\Delta\emptyset) \\ R \cos(\Delta\emptyset) \cos\theta_e - r \end{bmatrix}$$

The azimuth $\emptyset_o$ and elevation θ_o of a satellite relative to the earth station may be computed by a simple transformation from rectangular to spherical coordinates using:

$$\emptyset_o = \left[\tan^{-1} \frac{R_y'''}{R_x'''}\right] - n\pi$$

Where

$$n = \begin{cases} 0 \text{ southern hemisphere} \\ 1 \text{ northern hemisphere} \end{cases}$$

$$\theta_o = \tan^{-1} \frac{R_z'''}{\sqrt{R_x'''^2 + R_y'''^2}}$$

therefore,

$$\emptyset_o = \left[\tan^{-1} \frac{\tan(\Delta\emptyset)}{\sin\theta_e}\right] - n\pi \qquad (9\text{-}1)$$

$$\theta_o = \tan^{-1} \frac{\cos(\Delta\emptyset)\cos\theta_e - .151}{[1 - \cos^2\Delta\emptyset \cos^2\theta_e]^{\frac{1}{2}}} \qquad (9\text{-}2)$$

Equations 9-1 and 9-2 were used to calculate values of $\emptyset_o$ and θ_o corresponding to the extremities of CONUS for satellites #1 and #2 located at 80°W and 113°W longitude, respectively. These values are tabulated in Table 9-1 using the coordinate system referenced in Figure 9-2.

TABLE 9-1

SATELLITE COORDINATES

	LAT θ_e	LONG ϕ_e	$\phi_S = -80°$ SATELLITE #1 80°W LONG θ_o	ϕ_o	$\phi_S = -113°$ SATELLITE #2 113°W LONG θ_o	ϕ_o
Key West FL	25°	-82°	60.7°	-175.3° (184.7)	44.8°	-234.9° (125.1)
East Port ME	45°	-67°	36.6	-198.1 (161.9)	21.3	-235.7 (124.3)
Penasse MN	49.5	-95	31.5	-160.6 (199.4)	30.7	-203.1 (156.9)
Cape Flatters WA	49	-125	19.5	-127.0 (233.0)	32.6	-164.3 (195.7)
Imperial Beach CA	32.5	-117	35.3	-125.5 (234.5)	51.9	-172.6 (187.4)
Brownsville TX	25.5	-97.5	54.4	-143.8 (216.2)	55.5	-212.8 (147.2)

NOTE: Elevation θ_o and azimuth ϕ_o are referenced to North as shown in Figure 9-2. Angles in parenthesis are the positive equivalent of ϕ_o.

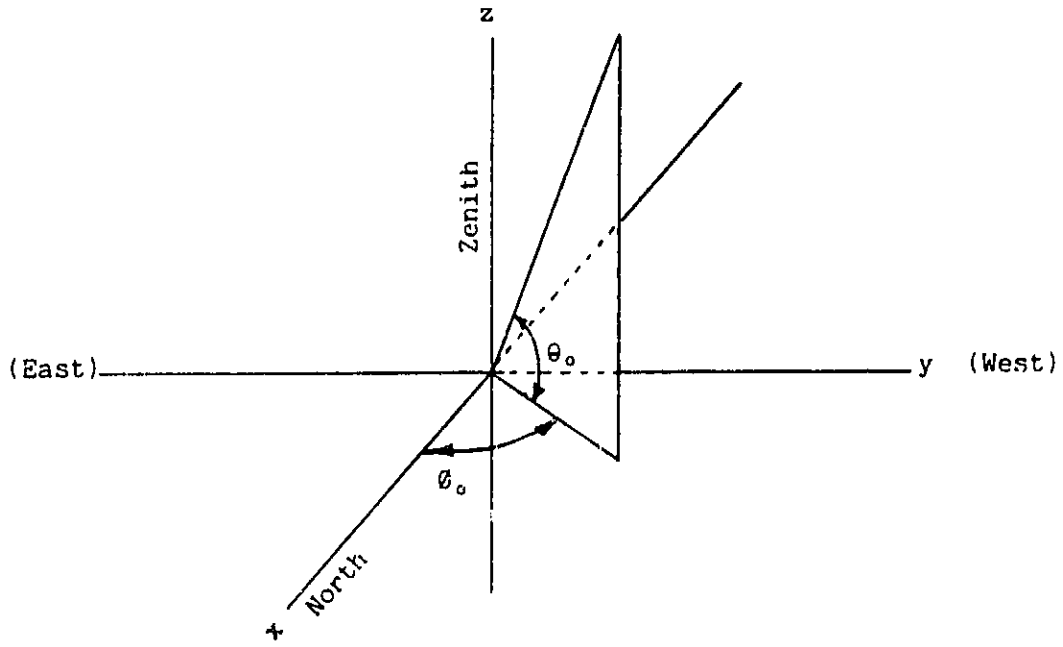


FIGURE 9-2

SATELLITE COORDINATES

9.3 Isolation Model.

The isolation model proposed here relies on the fact that any antenna directs a finite level of radiation through 4π steradians of space regardless of its fixed orientation. Therefore it is possible to model the relative radiation from a given antenna by a rectangular grid with limits of $\pm 180°$ in the ordinate and $\pm 180°$ in abscissa. The ordinate represents the azimuth angles ϕo of the preceeding section and the abscissa angles represent the elevation angles θo. At each point on the grid the relative radiation has a measured or calculatable value. Since earth stations are only located in CONUS elevation angles are limited to 0°-90° and azimuth angles range within the limits of +90° to +270°. The model is simplified to a grid shown in Figure 9-3.

The locations of the satellites calculated in Section 9-2 are added to the grid to complete the model. Note that there are two points designated by a (.) and (+) associated with each earth location.

To use this model to calculate isolation the grid which represents the radiation pattern of the e h station antenna must be modeled using the same grid as Figure 9-3. The peak radiation is arbitrarily set to zero dB and all other points on the grid are negative relative to the peak. This antenna pattern grid is then superimposed on the satellite grid (Figure 9-2) and positioned to place the peak (0 dB) point on the antenna grid at (or near) the position of the desired satellite. The isolation is then read directly from the antenna grid value nearest the "isolated" satellite of the satellite pair.

The remainder of this section is dedicated to establishing antenna pattern grid models for some of the antenna candidates. These are then used with Figure 9-3 to determine isolation estimates. In all candidates, except the planar arrays and parabolic reflector, the elevation angle of the antenna is assumed fixed at 40°. Therefore, the graphical solution based on a superposition of the two grids is simplified by placing the peak (0 dB point) on the 40° axis and sliding in azimuth only. The peak of the earth station beam will not necessarily coincide with the satellite intended for communication.

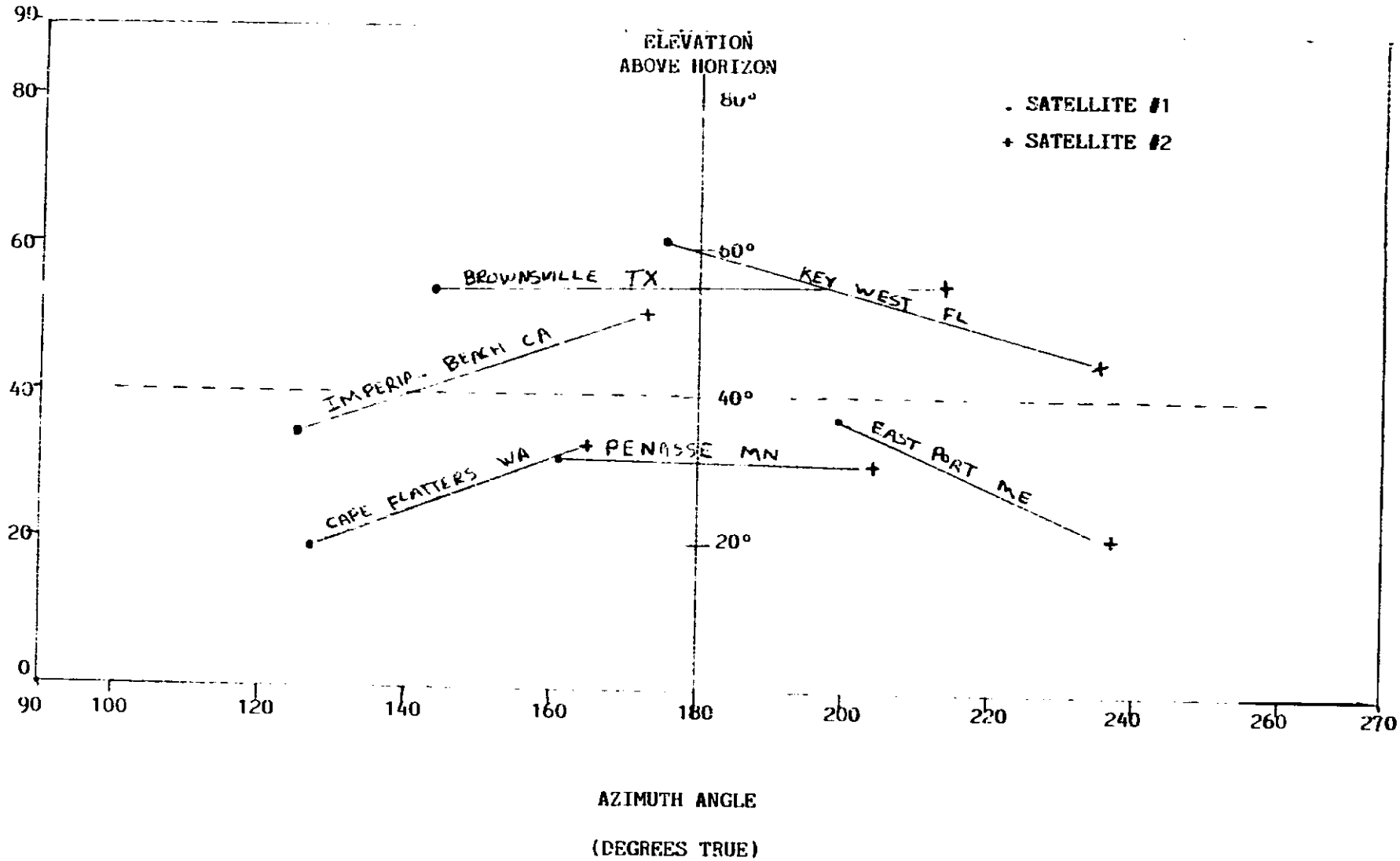


FIGURE 9-3. SELECTED SATELLITE COORDINATES

9.4 Isolation Calculation.

The key to these calculations is the formulation of an accurate antenna pattern grid. Various sources are available to help accomplish this goal.

a. Azimuth and elevation patterns for selected array elements are available.
b. Patterns for uniformly illuminated arrays are tabulated in the literature.[2]
c. Measured antenna patterns were used when ever possible.
d. Mathematical models of candidate antennas were used only when measured or tabulated data were not available.

9.4.1 Reflector Antenna.

Reflector type antennas discussed here are the corner reflector and parabolic reflector. The former is steerable in azimuth only while the latter is steerable in both azimuth and elevation.

9.4.1.1 Corner Reflector.

A photograph of a breadboard corner reflector is shown in Figure 4.1-5 with a measured elevation pattern in Figure 4.1-7. Using the principle of image elements[3] the azimuth pattern for the corner reflector antenna in Figure 4.1-5 may be computed using the following expression:

$$G(\emptyset) = 20 \text{ Log } \left[\frac{\cos (d \cos\emptyset) - \cos (d \sin \emptyset)}{} \right] \quad (9\text{-}3)$$

where:

$G(\emptyset)$ = the gain at azimuth angle $\emptyset$ relative to $G(0)$
d = the distance from the phase center of the feed to the apex of the corner reflector in radians
= $2\pi \ (.5) = \pi$

[2] Kraus, John, Antennas, McGraw-Hill, N.Y. 1950 pp. 520-521
[3] Ibid., p. 329

Using the elevation pattern data, the antenna grid model for the corner reflector appears as in Figure 9-4. All gain data appears as horizontal regions of constant gain relative to the peak in -dB since azimuth variation is not included. Similarly, by using only the azimuth data derived from equation 9-3 a grid with vertical gain regions will result (see Figure 9-5).

By assuming separability these two grids can be combined using simple addition to give a composite antenna pattern grid shown in Figure 9-6.

Isolation values for the corner reflector are estimated by the technqiue described in Section 9-3. These isolations are tabulated in Table 9-2.

TABLE 9-2

REFLECTOR TYPE ANTENNAS
(Isolation in dB)

Earth Station Location	Corner Reflector #1	Corner Reflector #2	Parabolic Reflector #1	Parabolic Reflector #2
Key West, FL	> 20	12.5	5	5
East Port, ME	18	12	2	2
Penasse, MN	19	19	2	2
Cape Flatters, WA	12	18	2	2
Imperial Beach, CA	20	19	4	4
Brownsville, TX	> 18	> 18	5	5
Worst Case	12	12	2	2

Isolation numbers were evaluated for each satellite for each earth station location from Table 9-1. For instance, a station at East Port, Maine, communicating with satellite #1 will be isolated from satellite #2 by 12 dB. Conversely, if this same station were communicating with satellite #2, its isolation from satellite #1 would be 18 dB.

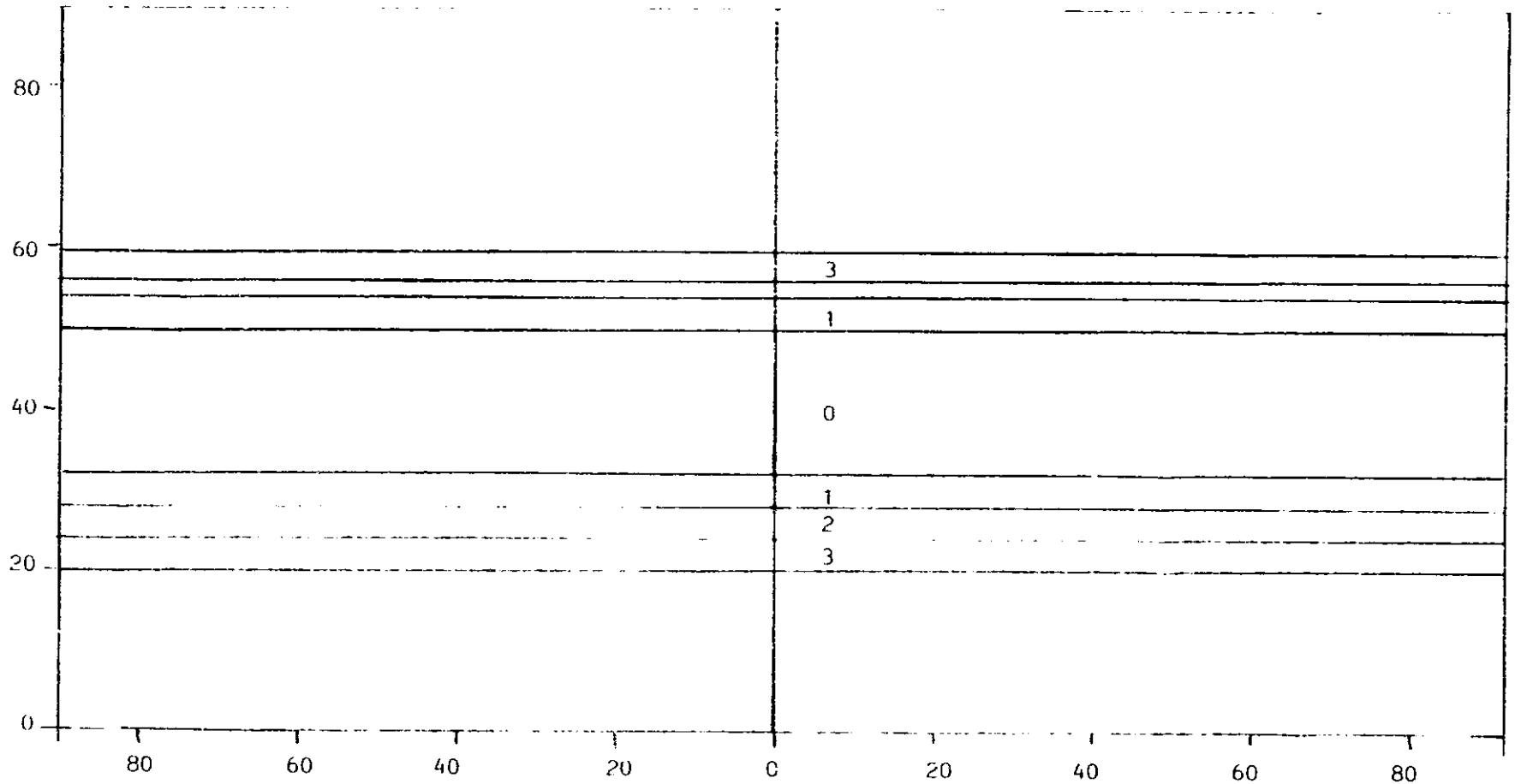


FIGURE 9-4. CORNER REFLECTOR ELEVATION PATTERN

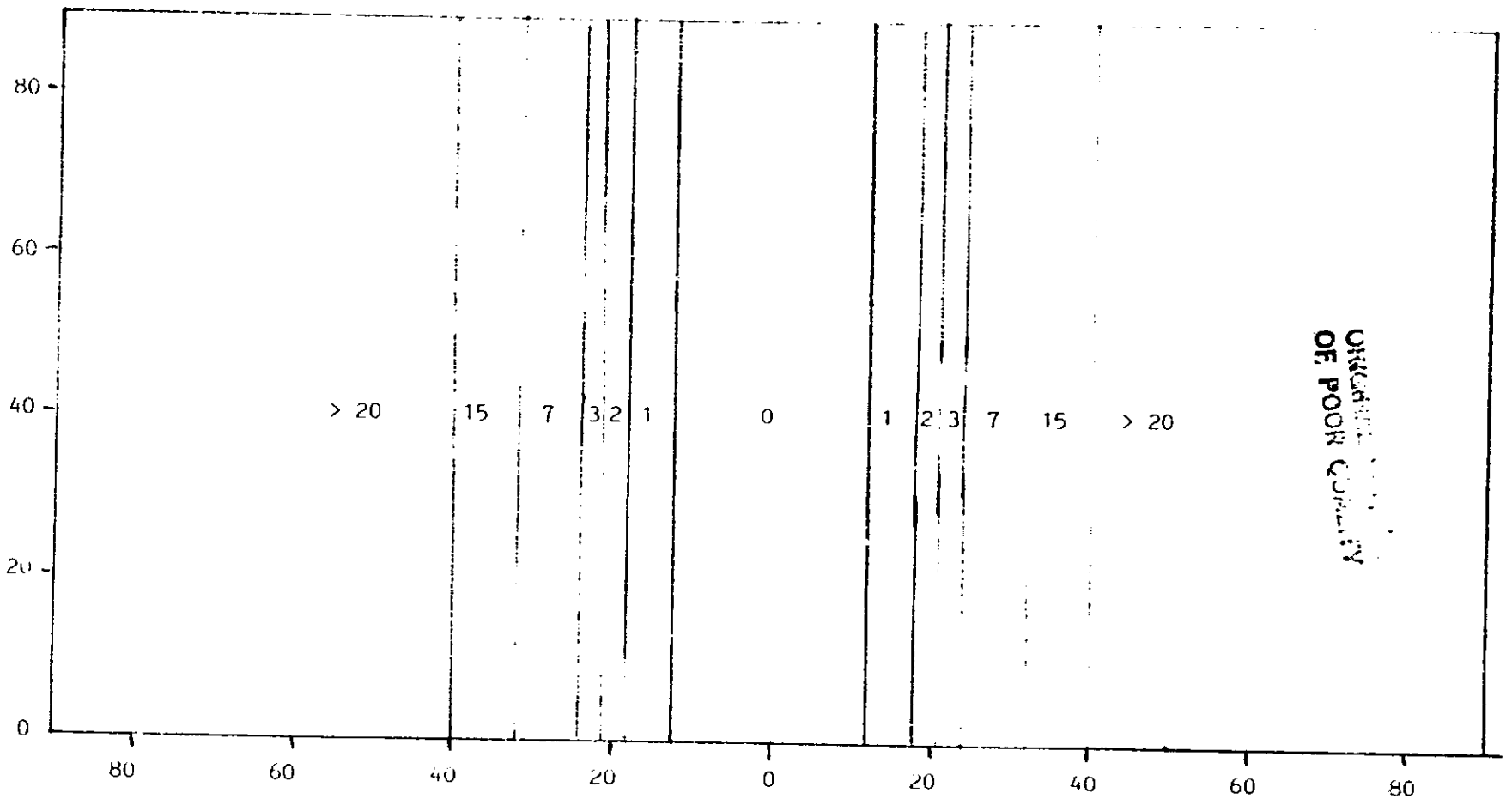


FIGURE 9-5. CORNER REFLECTOR AZIMUTH PATTERN

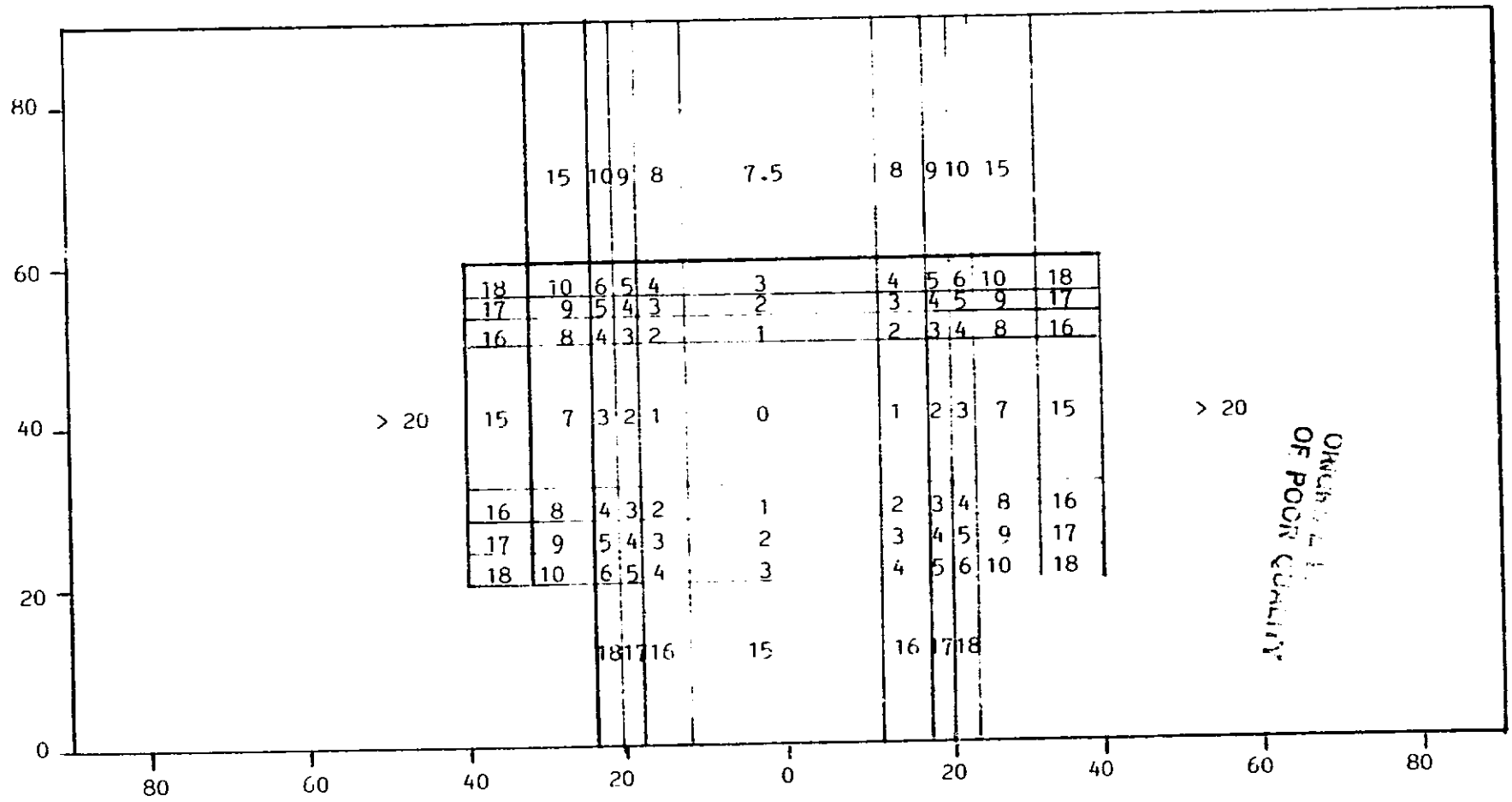


FIGURE 9-6. CORNER REFLECTOR

9.4.1.2 Parabolic Reflector Antenna.

A typical parabolic reflector candidate is shown in Figure 8.3-1. Since no measured data was taken for this candidate it is necessary to compute the azimuth and elevation patterns based on an assummed illumination of the given reflector and use these to construct the antenna grid model.

The following assumptions are made in computing the isolation for the parabolic antenna:

a. Because of elevation scanning capability the peak of the beam can be placed precisely on the desired satellite.

b. Only the smallest reflector (12" x 14") is analyzed because it is assumed that isolation will improve with dish size.

c. A cosine illumination is assumed and gain pattern is given by the expression:

$$G(\emptyset) = 20 \log \left[\frac{(\pi/2)^2 \cos [(D \sin \emptyset)/2]}{(\pi/2)^2 - [(D \sin \emptyset)/2]^2} \right] \qquad (9\text{-}4)$$

$$D = \begin{cases} 2\pi\ (12/\lambda) = 1.7\pi & \text{for elevation} \\ 2\pi\ (14/\lambda) = 1.9\pi & \text{for azimuth} \end{cases}$$

$G(\emptyset)$ = the gain at angle (azimuth/elevation) $\emptyset$ relative to $G(0)$

Figure 9-7 shows an antenna grid model for the 12" x 14" parabolic reflector. Calculation of the values for elevation and azimuth were made separately and combined as for the corner reflector. Isolations for selected locations in CONUS are tabulated in Table 9-2.

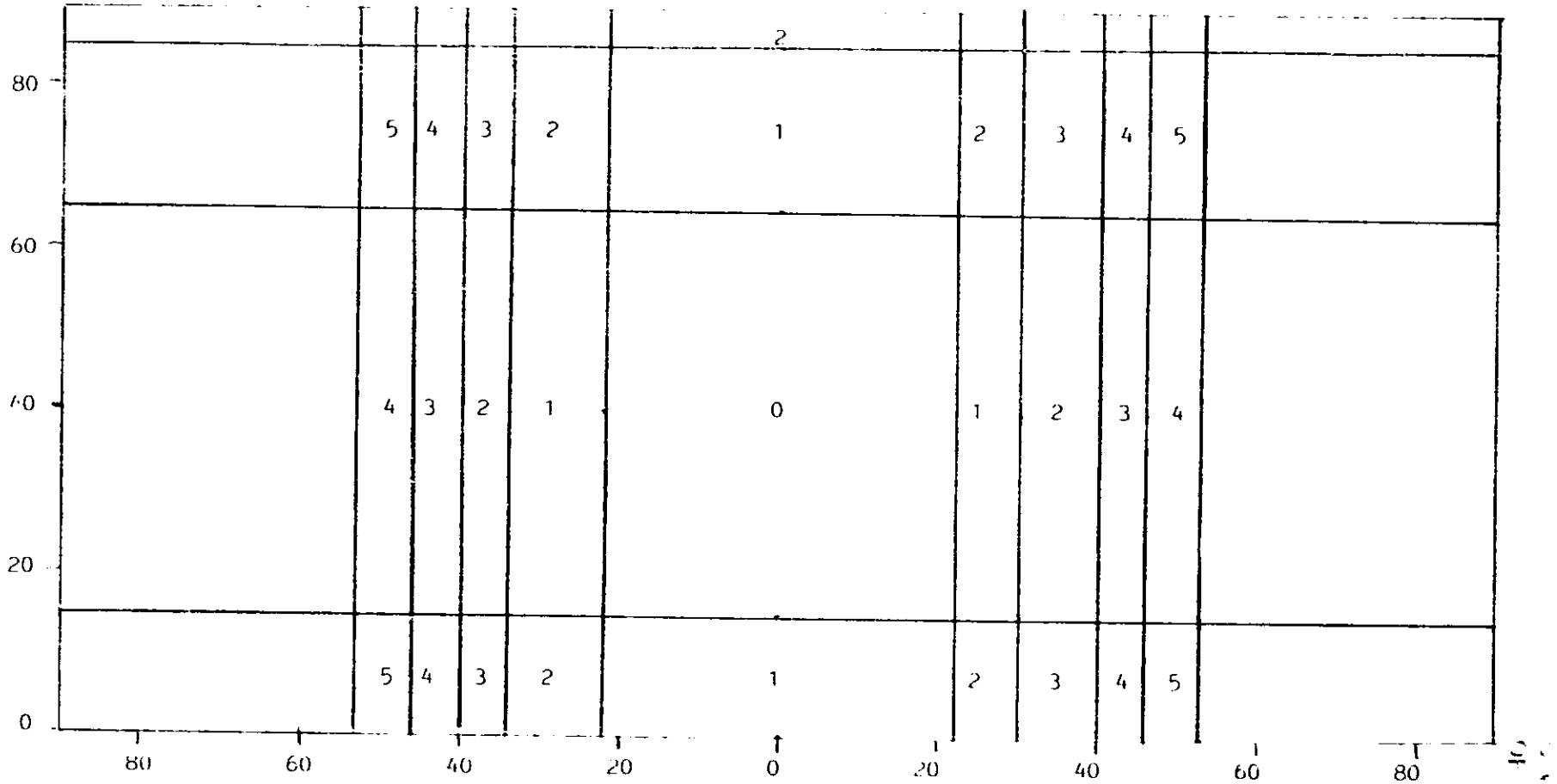


FIGURE 9-7. 12" x 14" REFLECTOR W/COSINE ILLUMINATION

9.4.2 Linear Array Antenna.

Linear arrays using different types of elements have been discussed in this report, and linear arrays of single elements and linear arrays of double elements have been suggested. This section shall present isolation calculations for arrays of each of the following types of array elements:

a. Six-turn helix elevated to a 30° tilt angle
b. Cross slot
c. Horn elevated to 40°

Measured elevation data for the first two types are available in this report. Horn data shall be determined using curves in the literature. Azimuth data needed to model these arrays is based on a simple graphical solution using published patterns for uniformly illuminated arrays[4] (see Figure 9-8)

9.4.2.1 Helix Array.

Two array configurations shall be analyzed for isolation: a linear array of two helices with $\lambda/2$ spacing (Figure 8-2) and a linear array of four helices with $\lambda/2$ spacing.

The antenna grid model for each array is obtained by the following steps:

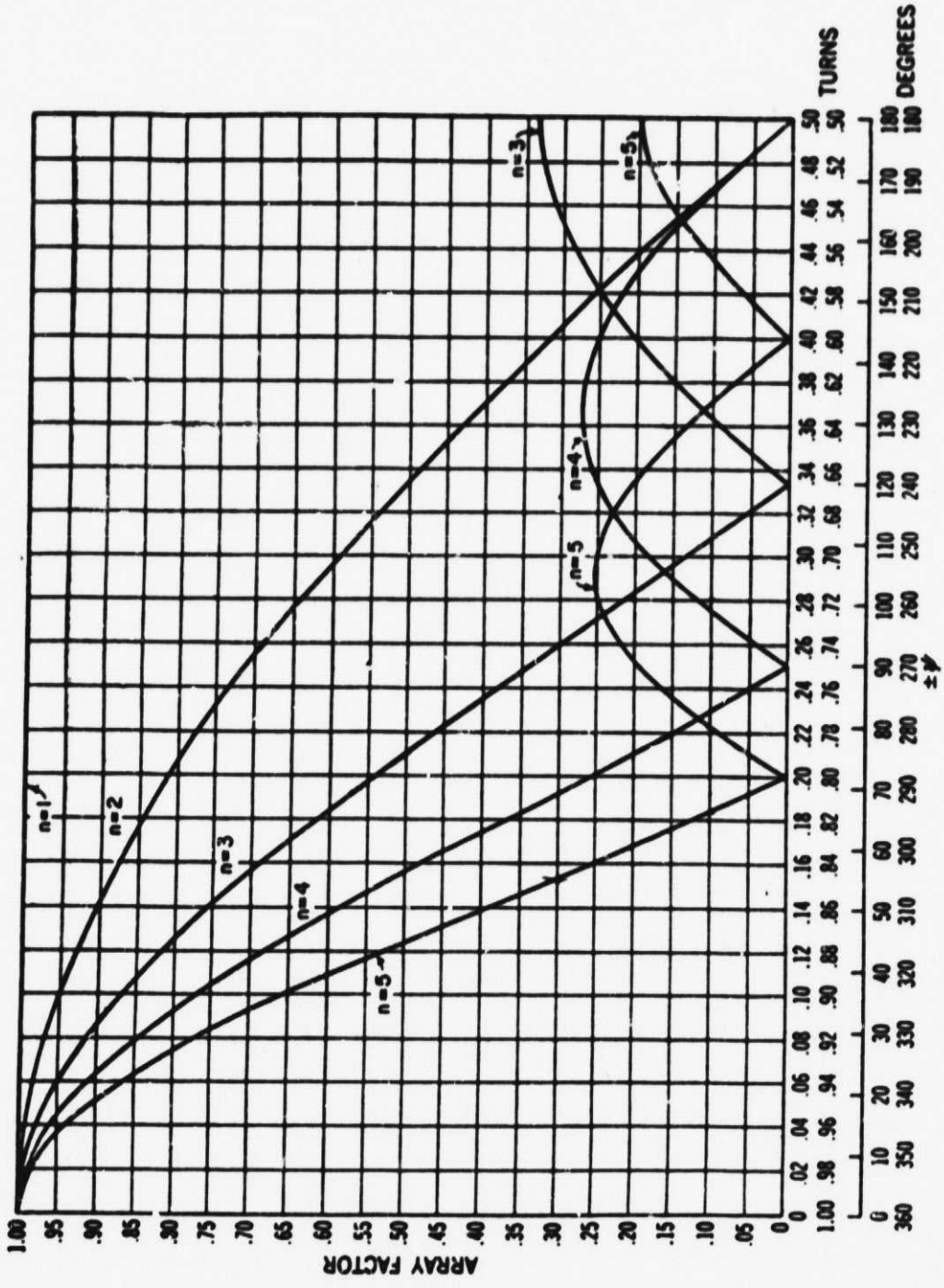
Step 1 Elevation primary pattern data comes from measured data in Figure 4.2-1.

Step 2 The azimuth pattern is estimated by using a graphical solution for uniformly illuminated array of isotropes. (Figure 9-8)

Step 3 Azimuth pattern is refined by factoring in the element azimuth pattern derived using a parabolic approximation (Figure 9-9). For this step a helix with the following characteristics is assumed.

[4] Ibid. pp. 520-534

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$\psi = d_\lambda \sin \phi$

FIGURE 9-8. ARRAY FACTOR COMPUTATION

PARABOLIC APPROXIMATION

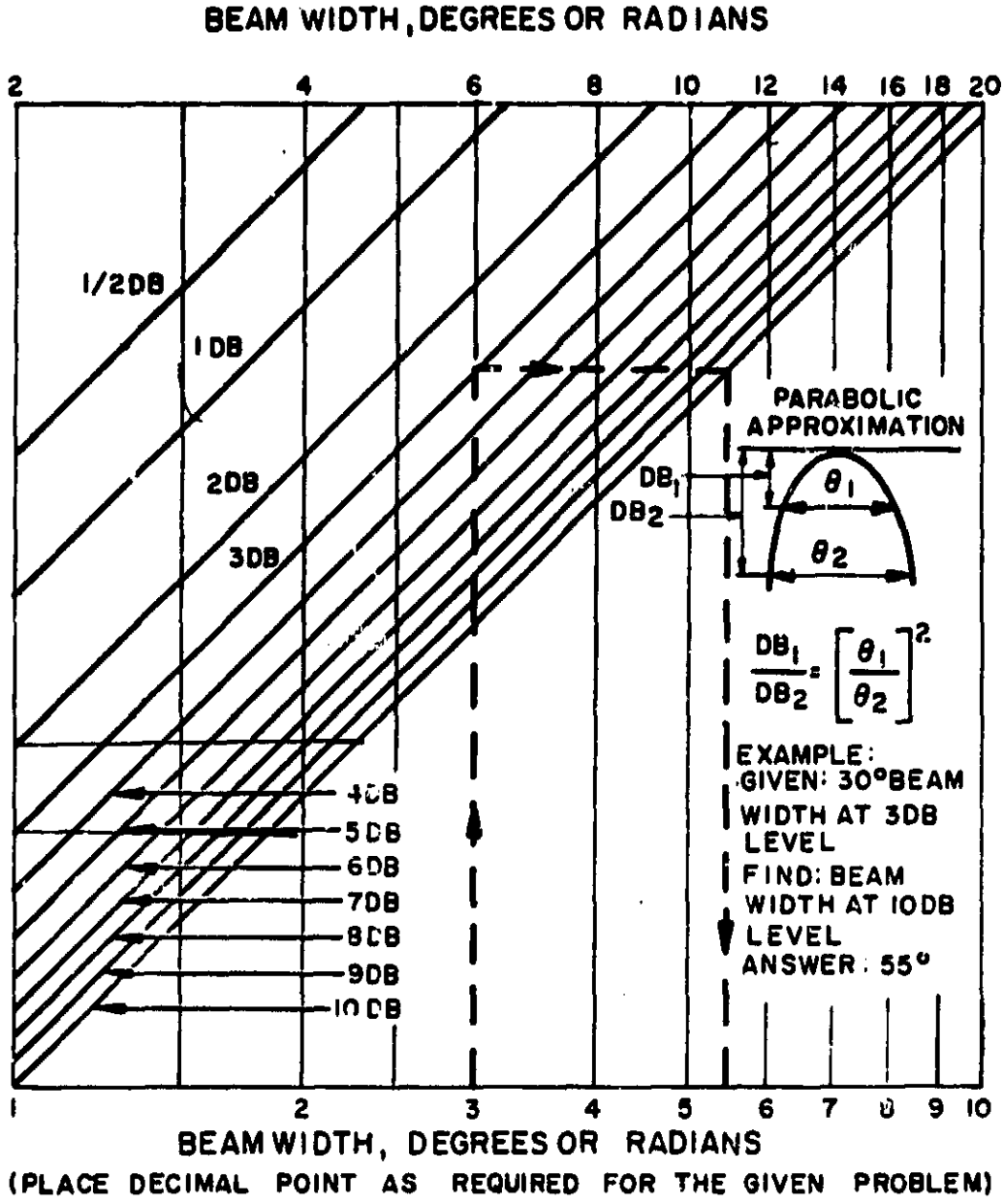


FIGURE 9-9. HELIX & HORN PATTERN COMPUTATION

$$\text{3 dB beamwidth} \simeq \frac{52}{C_\lambda \sqrt{nS_\lambda}} \text{ deg.}$$

where,

C_λ = circumference in wave lengths = 1

nS_λ = axial length in wavelengths = (6)(.3) = 1.8

$\therefore$ 3 dB beamwidth $\simeq$ 38.8°

Step 4 Antenna grid model is developed as in Section 9.4.1.1

The results of this process for a two-element and a four-element array of helices is shown in Figures 9-10 and 9-11, respectively. These grid models are then used to determine the isolation values in Table 9-3 for several locations in CONUS.

TABLE 9-3. LINEAR ARRAYS

(Isolated in dB)

	HELIX ARRAY				CROSS SLOT		HORN ARRAY			
	1 X 2		1 X 4		2 X 5		1 X 4		2 X 4	
EARTH STATION	#1	#2	#1	#2	#1	#2	#1	#2	#1	#2
Keywest, FL	>19	>20	>19	20	>20	21	20	20	>18	>20
East Port, ME	7	7	15	15	19	20	15	15	16	13
Penasse, MN	18	18	20	20	15	15	13	13	13	13
Cape Flatters, WA	7	7	15	15	19	14	14	16	13	17
Imperial Beach, CA	19	7	29	>19	>20	20	13	13	14	12
Brownsville, TX	20	20	20	20	14	14	20	20	20	20
WORST CASE	7	7	15	15	14	14	13	13	13	12

9.4.2.2 Cross Slot Array.

A 2 x 5 element array similar to that shown in Figure 8-1 is analyzed here using the graphical approach introduced in Section 9.4.2.1. The basic array factor calculations for azimuth and elevation are refined by factoring in measured element pattern values shown in Figure 4.5-1. The azimuth patterns are approximated using the curves in Figure 9-8 (n=5) and assuming $\lambda/2$ spacing and uniform illumination. The array elevation pattern is approximated using the curves in Figure 9-8 (n=2). Figure 9-12 shows the antenna grid used to determine the isolations in Table 9-3 for the cross slot array.

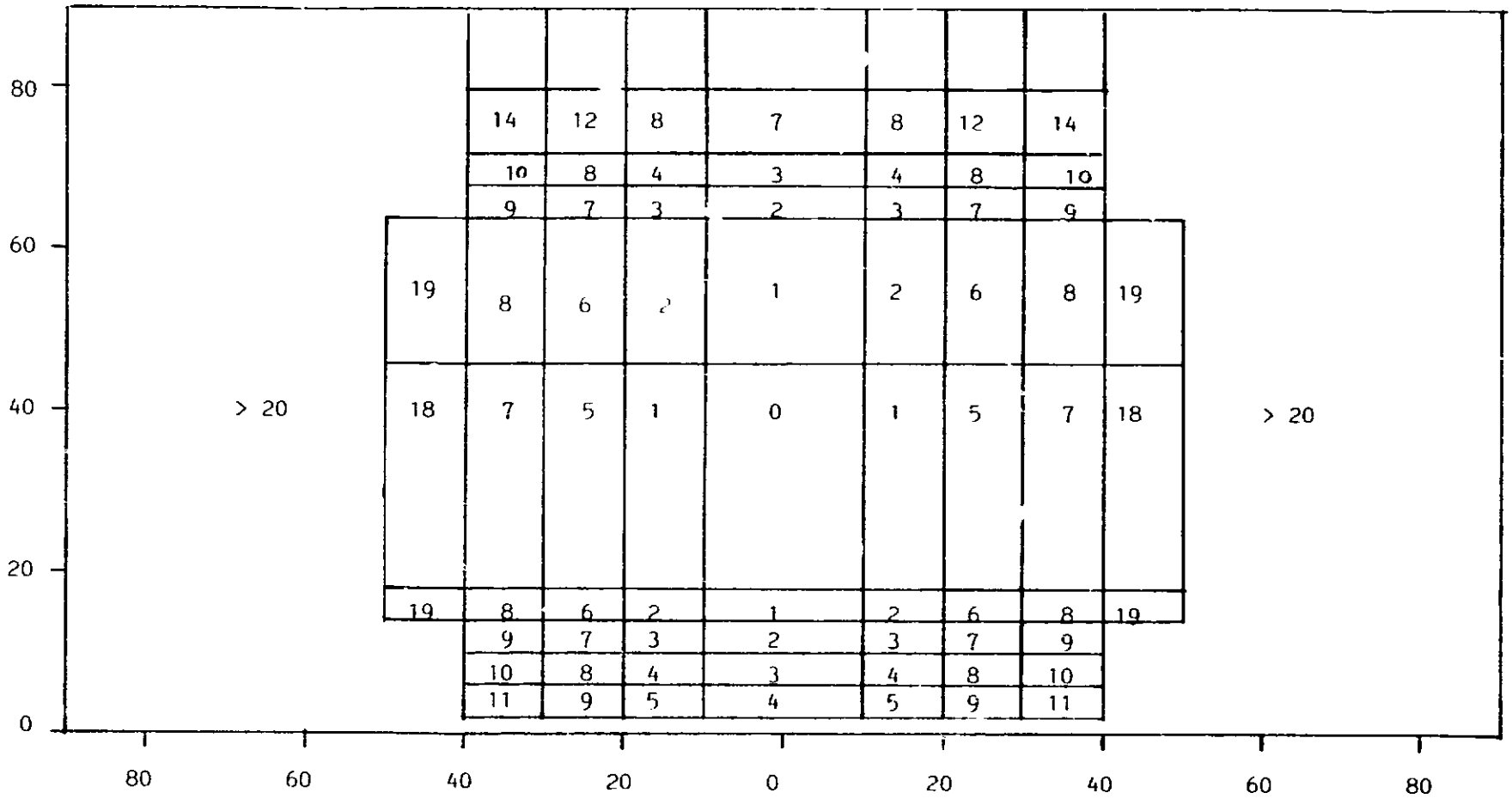


FIGURE 9-10. 1 X 2 HELIX ARRAY

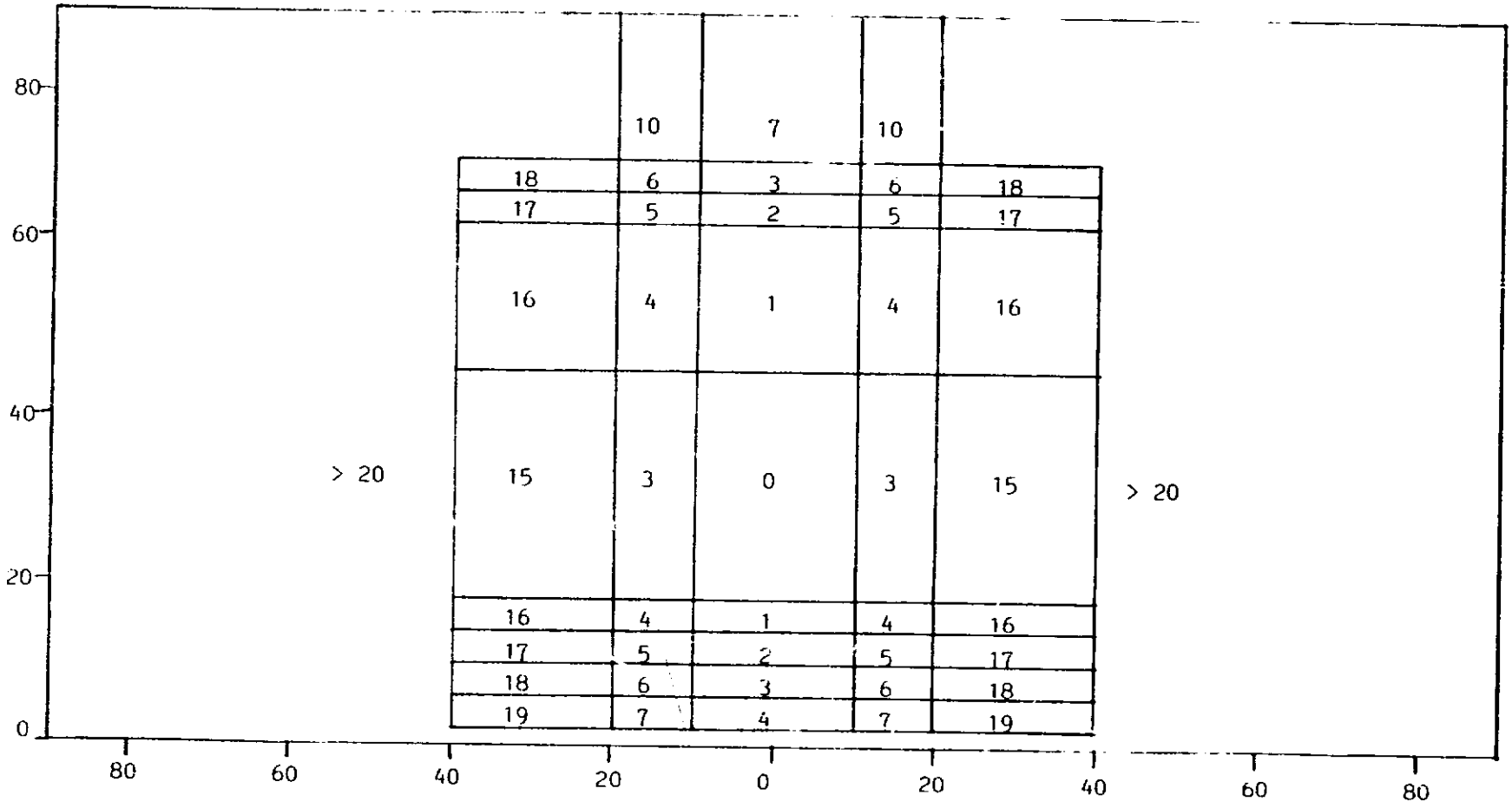


FIGURE 9-11. 1 X 4 HELIX ARRAY

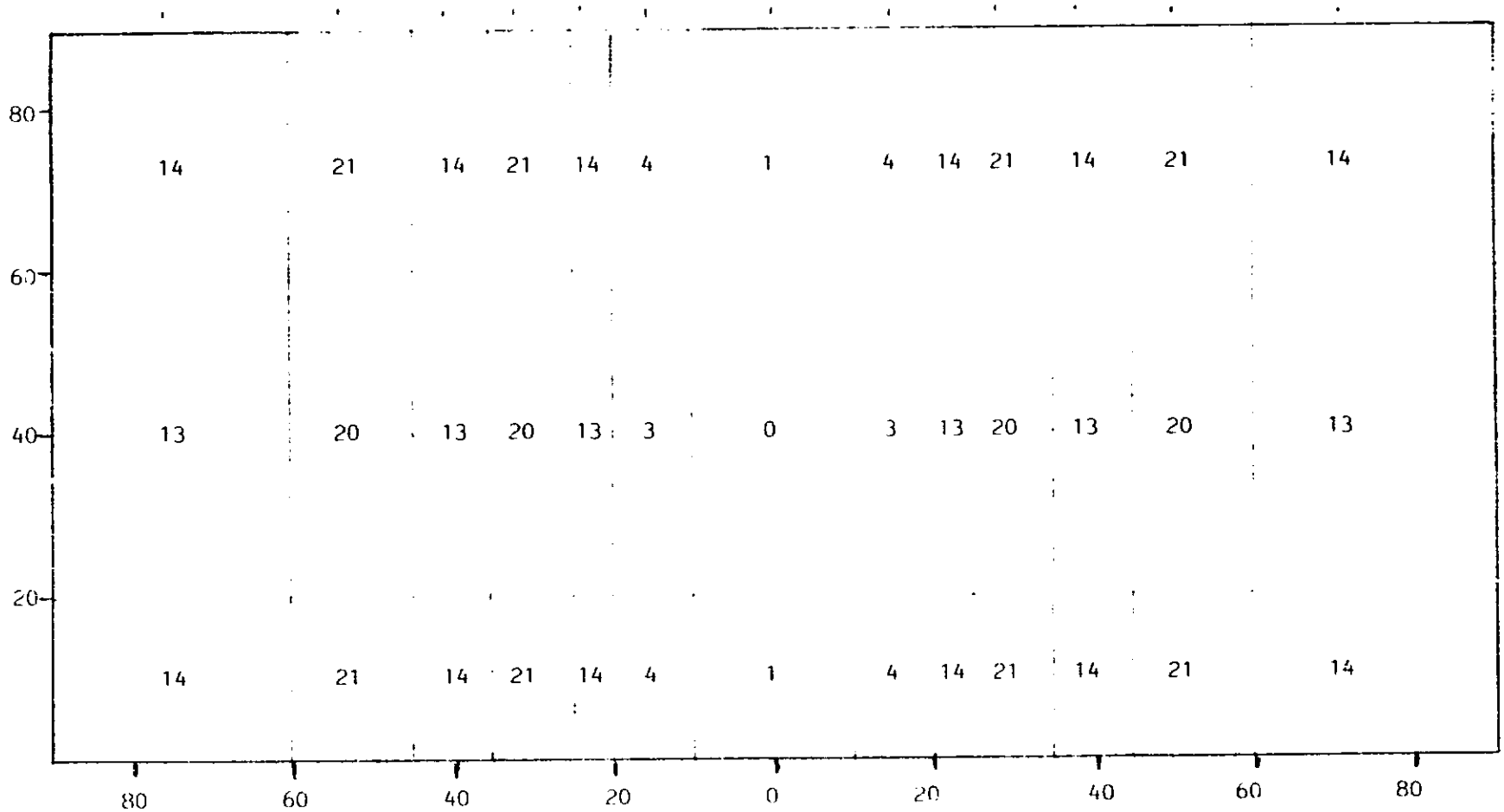


FIGURE 9-12. 2 x 5 CROSSED SLOT ARRAY

OF POOR QUALITY

9.4.2.3 Horn Array.

Two horn arrays have been proposed: a 1x4 linear array (Figure 8.4-1) and a 2x4 linear array (Figure 8.4-2). No measured pattern data is available to assist in developing the anterna grid model. Therefore, the azimuth and elevation patterns for the horns are computed using an assumed aperture size. Table 9-4 relates the 3 dB beamwidths to the horn size. These 3 dB beamwidths are used with Figure 9-9 to calculate azimuth and elevation patterns.

TABLE 9-4

HORN 3-dB BEAMWIDTHS

	3-dB Beamwidths	
Horn Size	Azimuth	Elevation
8.5" x 11.0"	110°	71.5°
8.5" x 6.75"	110°	116.5°

Figures 9-13 and 9-14 are the antenna grid models for the 1x4 array and 2x4 array, respectively. These models were used to determine the isolation figures in Table 9-3.

9.4.3 Planar Array.

The isolation estimation for a conformal planar array shall be confined to a simple mathematical modeling of the roof top array as a rectangular array of 36 elements (Figure 9-15). The elements are assumed to be fed with a uniform illumination and a phase progression necessary to steer the main beam directly at the selected satellite. A graphical technique described below is used to approximate the array pattern amplitude in the direction of the isolated satellite with respect to the amplitude at the selected satellite.

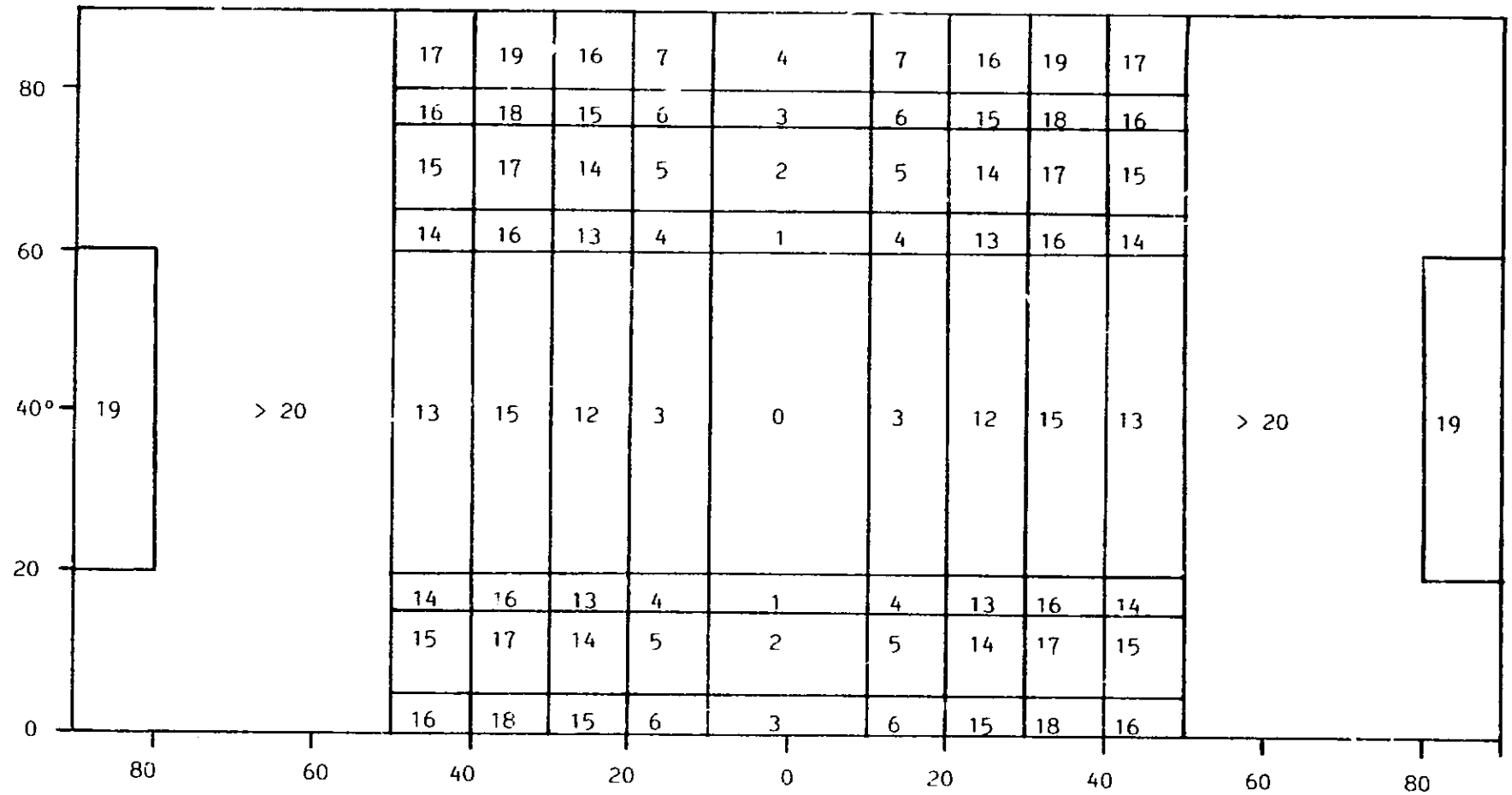


FIGURE 9-13. 1 X 4 HORN ARRAY

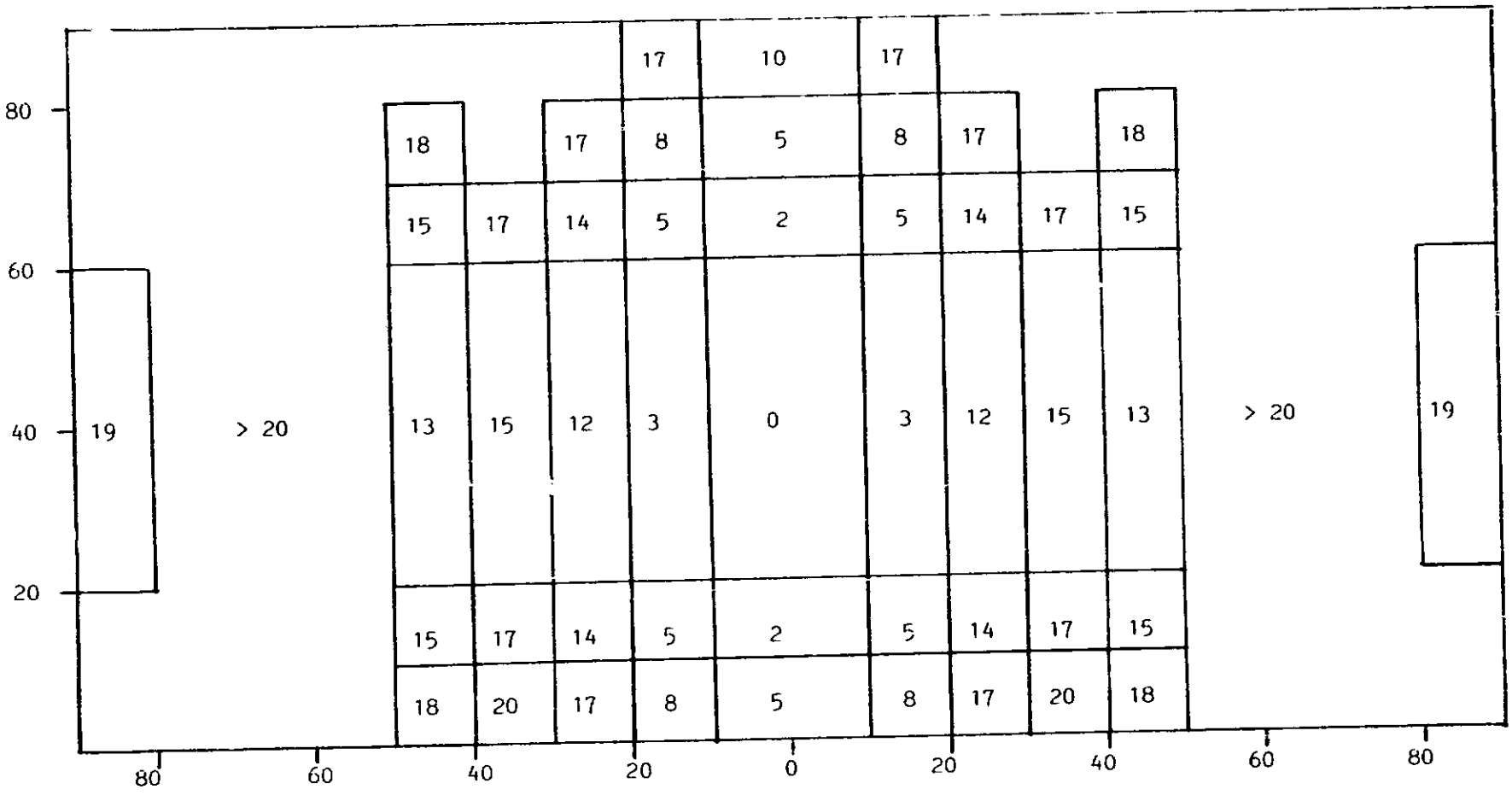


FIGURE 9-14. 2 X 4 HORN ARRAY

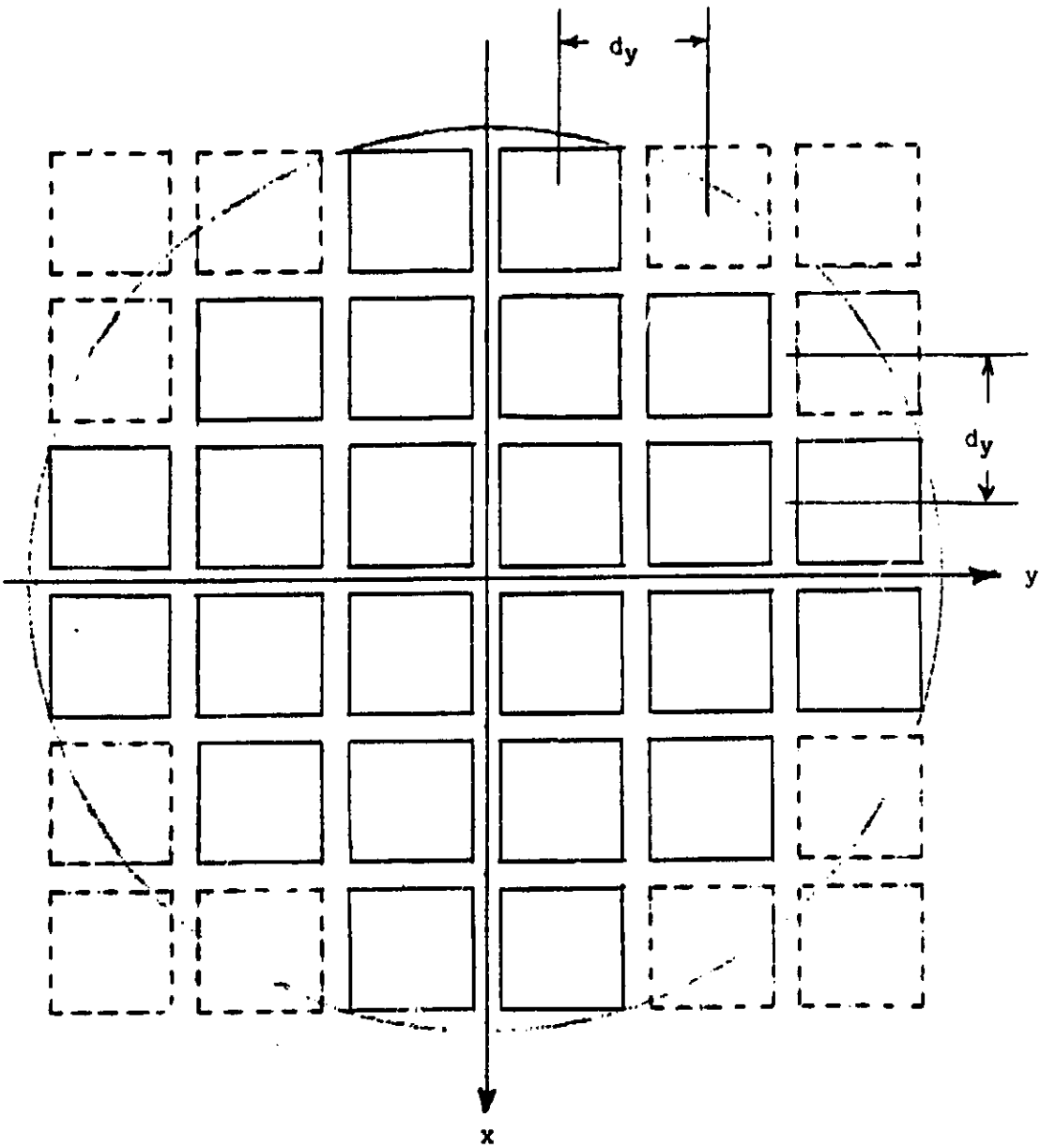


FIGURE 9-15. RECTANGULAR PLANAR ARRAY

9.4.3.1 Phase Shift Calculations

Assumptions:

(1) A planar 6-by-6 element array with .42λ element spacing. (Figure 9-15)

(2) Current distribution is separable allowing for computing of the phase shifts in the $\bar{u}''_x$ direction and $\bar{u}''_y$ direction separately.* Therefore, the array factor is defined as:

$$A(\theta,\emptyset) = A_x(\theta,\emptyset)\, A_y(\theta,\emptyset) \qquad (9\text{-}5)$$

where,

$$A_x(\theta,\emptyset) = \sum_{-N_x}^{+N_x} I_m e^{jm(kd_x \cos\theta \cos\emptyset - \alpha_x)}$$

$$A_y(\theta,\emptyset) = \sum_{-N_y}^{+N_y} I_n e^{jm(kd_y \cos\theta \sin\emptyset - \alpha_y)}$$

For the special case being analyzed:

$$d_x = d_y = .42\lambda$$

$$I_m = I_n = 1$$

$$N_x = N_y = 3$$

There is a constant phase taper across the array in the +X direction of α_x and a constant phase taper across the array in the +Y direction of α_y.

It can be shown that the array described above will place a main beam at $(\theta_o, \emptyset_o)$ if the following equations are satisfied:

$$\alpha_x = kd_x \cos\theta_o \cos\emptyset_o \qquad (9\text{-}6a)$$

$$\alpha_y = kd_y \cos\theta_o \sin\emptyset_o \qquad (9\text{-}6b)$$

* $\bar{u}''_x$ and $\bar{u}''_y$ refer to the North and West directed unit vectors at the Earth Station location.

Substituting

$$d_x = d_y = .42\lambda$$

$$k = 2\pi/\lambda$$

Into equations 9-6a/9-6b gives:

$$\alpha_x = .84\,\pi \cos\theta_o \cos\phi_o \qquad (9\text{-}7)$$
$$\alpha_y = .84\,\pi \cos\theta_o \sin\phi_o$$

Table 9-5 shows computed values for α_x and α_y for the earth locations listed in Table 9-1.

TABLE 9-5
PLANAR ARRAY PHASE SHIFT DATA

	Phase shift to place main beam on Satellite #1		Satellite #2	
	α_{x_1}	α_{y_1}	α_{x_2}	α_{y_2}
Key West, FL	73.7	6.0	61.7	-87.8
East Port, ME	115.4	-37.7	79.4	-116.4
Penasse, MN	121.6	42.8	119.6	-51.0
Cape Flatters, WA	85.8	113.8	122.6	34.5
Imperial Beach, CA	71.7	100.5	92.5	12.0
Brownsville, TX	71.0	52.0	72.0	-46.0

9.4.3.2 Pattern Calculations

Figure 9-15 shows a candidate array which consists of a 6-by-6 array truncated at the corners to give it a nearly round shape. The initial analysis of the array will be as a 6-by-6 element square with separable X and Y axis illumination. Although lacking in completeness, this approach is quick and simple and can serve as a good first approximation.

The technique uses the fact that a separable excitation in the X and Y axis will result in an array factor which is separable into the product of two conical beams which form a main beam in the +Z hemisphere wherever they intersect. The analysis shall be as follows:

a) The coordinates θ_o, ϕ_o of the satellite desired for communication are substituted into equation 9-6a and equation 9-6b to give α_x and α_y (Table 9-5).

b) The angles θ_x and θ_y of the two conical beams with respect to the X and Y axis respectively necessary to give a main beam at (θ_o, ϕ_o) are computed using the relationships:

$$\sin \theta_x = \frac{\alpha_x}{kd_x} = \sin \theta_o \cos \phi_o$$

and

$$\sin \theta_y = \frac{\alpha_y}{kd_y} = \sin \theta_o \sin \phi_o$$

c) The two conical beam patterns are calculated using the array factor for a six element linear array (Figure 9-16) rotated about the X axis and Y axis respectively. The value for ψ is given as:

$$\psi_x = kd_x \sin \theta \cos \phi - \alpha_x$$

and

$$\psi_y = kd_x \sin \theta \cos \phi - \alpha_y$$

For the desired satellite $\psi_x = \psi_y = 0$. If $d_x = d_y = .42\lambda$, the ψ for the isolated satellite is given as:

$$\psi_x = .84\pi \sin \theta_2 \cos \phi_2 - \alpha_x = \alpha_{x_2} - \alpha_{x_1}$$

and

$$\psi_y = .84\pi \sin \theta_2 \sin \phi_2 - \alpha_y = \alpha_{y_2} - \alpha_{y_1} \qquad (9\text{-}8)$$

Where θ_2 and ϕ_2 are the coordinates of the second satellite with respect to the array. The phase shifts necessary to place the main beam on the first satellite are α_{x_1} and α_{y_1}.

Using these values for ψ, the array factor for the X and Y axis conical beams are read from Figure 9-16 as AF_x and AF_y. The isolation (radiation) at the second satellite with respect to the main satellite is given as:

$$I = 20 [\log (AF_x) + \log (AF_y)]$$

The following is a sample calculation of the isolation for an earth-based antenna located in Key West, Florida, communicating with a satellite at 80°W longitude.

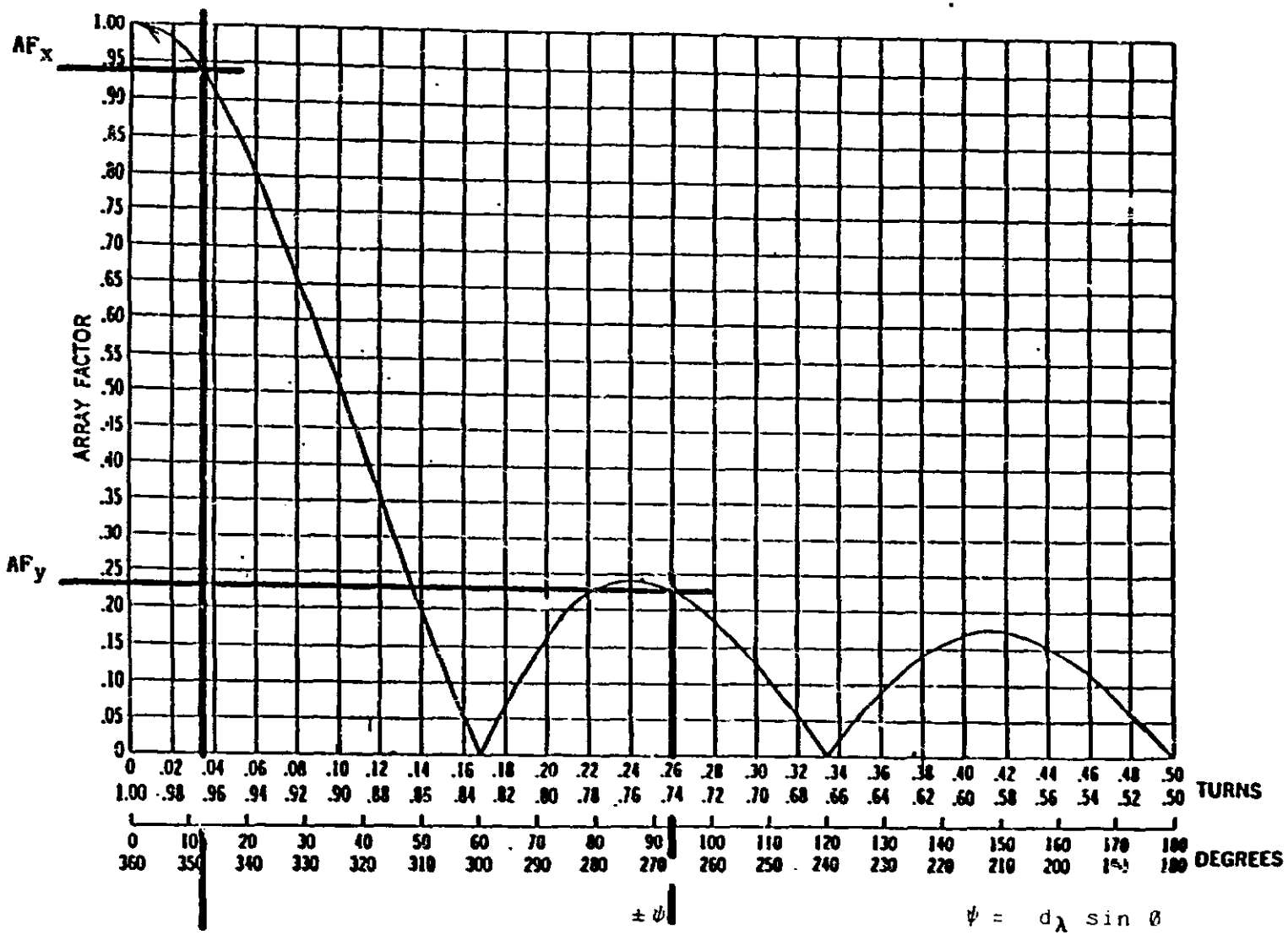


FIGURE 9.16. SIX-ELEMENT ARRAY FACTOR COMPUTATION

From Table 9-5:

$$\alpha_{x_1} = 73.7$$

$$\alpha_{y_1} = 6.0$$

$$\alpha_{x_2} = 61.7$$

$$\alpha_{y_2} = -87.8$$

Using equation (9-8): $\psi_x = 61.7 - 73.7 = -12.0°$

$\psi_y = -87.8 - 6.0 = -93.8°$

From Figure 9-16: AF $(\psi_x) = 0.94$

AF $(\psi_y) = 0.23$

Therefore, isolation = 20 [log (.94) + log (.23)]

= -13.4 dB

The isolation figures in Table 9-6 represent a range of isolation figures to be expected as the array is moved throughout CONUS. It is expected that worstcase isolation shall be -13.4 dB based on this simple square array model using uniform illumination.

TABLE 9-6

PLANAR ARRAY ISOLATION

	Isolation	$\lvert\psi_x\rvert$	$\lvert\psi_y\rvert$
Key West, FL	-13.4	12.0	93.8
East Port, ME	-18.8	36.0	78.7
Penasse, MN	-12.5	2.0	93.8
Cape Flatters, WA	-18.8	36.8	79.3
Imperial Beach, CA	-14.2	20.8	88.5
Brownsville, TX	-14.0	1.0	98.0

9.4.3.3 Data Refinement

The following refinements are suggested to provide more accurate isolation predictions.

a. A triangle arrangment rather than a rectangular arrangement of array elements should be used (Figure 9-17).

b. A tapered illumination such as a 20 dB sidelobe Tchebycheff should be substituted for the uniform illumination used in Section 9.4.3.2.

c. Pattern isolation should be calculated by summing the contributions due to all the individual elements.

d. Element pattern data should be used to enhance the isolation predictions.

9.4.4 Ring Array

A typical ring array configuration is shown in Figure 10-1. Because of the variations available, this candidate has not been analyzed in detail. In general the uniformly illuminated ring array should have isolation similar to the linear arrays.

9.4.5 Isolation Enhancement Techniques

There are three practical techniques which may render the secondary satellite insensitive to signals sent to the primary satellite; illumination tailoring, shielding and polarization diversity. Each has it own limitations and practical applications based on the individual antenna candidate and the degree of isolation improvement desired.

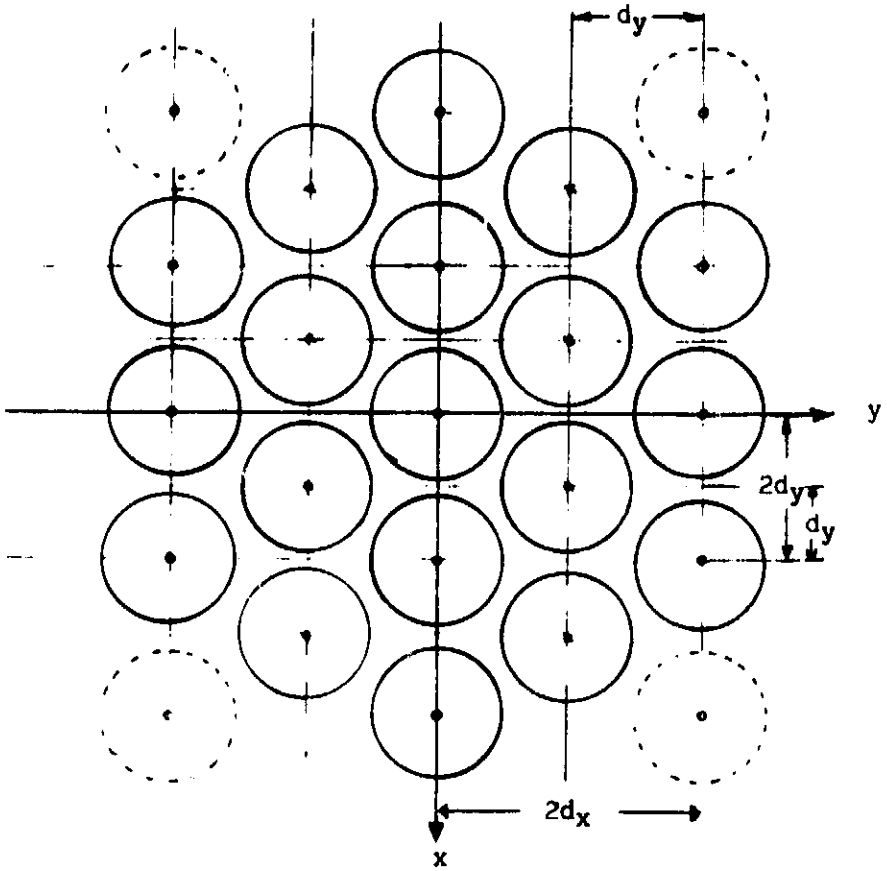


FIGURE 9-17. TRIANGULAR PLANAR ARRAY

9.4.5.1 Illumination Tailoring

This technique is most practical with arrays of greater than three elements. It relies on the fact that pattern shape is dependent on the relative phase and amplitude of the driving currents across an antenna aperture. By using amplitude tapers on the array illumination, all sidelobes can be set to levels which will provide the required 20 dB isolation. The optimum amplitude distribution is the Dolph Tschebysheff which has the highest directivity for the lowest sidelobes level. With this distribution, all sidelobes have equal levels. If the sidelobe level is set to 18 dB, the directive loss becomes 0.2 dB. Polarization discrimination will then generally increase the isolation by 3.5 dB so the total isolation will be over 20 dB.[5] Table 9-7 summarizes how illumination tailoring may be used to enhance each of the candidate antennas.

TABLE 9-7
Illumination Tailoring

Candidate Antenna	Technique	Isolation Improvement
Parabolics	Because of the dish size and the feed design illumination enhancement is of little value.	0 dB
1 & 2 element corner	Not practical	0 dB
2 element helix	Array factor isolation can be improved by 4.36dB by changing helix spacing to 0.6 λ. This may cause significant gain and pattern degradation.	4.36 dB
4 element helix	Same as above with illumination taper	4.0 dB
2x5 element crossed slot	Tapered illumination, placing ~0.8 edge element excitation, will tend to lower sidelobes and move the first null.	4-5 dB
4 element horn 2x4 element horn	Tapering illumination appropriately and increasing spacing may provide 1-2 dB.	1-2 dB
Ring array		4-5 dB
Planar array	Phase shifters and μ processor control lends itself to illumination tailoring. Tapering will lower sidelobes and move nulls.	4-6 dB

[5] Brown, B. Lawrence, Sharp, Gleen A., "Tschebysheff Antenna Distribution, Beamwidth and Gain Tables", Navaro Report 4629 , 1958.

9.4.5.2 Shielding

Techniques which either block radiation in the direction of the undesired satellite or place a null in this direction or direct energy away from this satellite are considered as shielding techniques.

The most obvious shield is a sheet of absorbing material which can move with the radome or be aligned with the undesired satellite after acquisition of the desired satellite.

A more subtle technique uses a corrugated surface aligned at 36° with respect to the peak of the beam thus forcing a minimum of radiation along the plane of the shield in the general direction of the undesired satellite. This, of course, would have to be used for a horizontally polarized field and converted to circular following the shield.

Directors and reflectors are elements which are placed to scatter or direct energy away from the undesired satellite. These present a simple implementation of shielding. Table 9-8 summarizes how shielding may be used to enhance each of the candidate antennas.

TABLE 9-8 - Shieldin

Antenna	Shielding Techniques	Isolation Improvement
Parabolic	Use positionable absorber on radome or use a spoiler on the dish.	
1 & 2 element corner	Absorber patch and director or reflector element.	~5 dB
2 element helix	See Table 9-9	?
4 element helix	Use positionable absorber	~5 dB
2x5 element crossed slot	Use positionable absorber on radome	~5 dB
4 element horn and 2x4 element horn	Same as above	~5 dB
Ring array and Planar array	not practical	—

9.4.5.3 Polarization Diversity

Table 9-9 summarizes how polarization diversity can be used to enhance isolation for each of the candidate antennas. This scheme assumes that the two satellites are sensitive to orthogonal senses of circular polarization. Right hand circular polarization (CP) sent to the first satellite would be invisible to the second satellite which receives only left hand CP and vice-versa. Because off-axis polarization is not as pure as main beam polarization, one cannot expect the infinite isolation that theory predicts. In practice, 3-6 dB is the maximum improvement that can be expected.

TABLE 9-9 POLARIZATION DIVERSITY

Antenna	Techniques	Isolation Improvement
Parabolic	Dual polarized feed?	?
1 & 2 element corners	Not practical	-
Ring array and Planar array	Use dual polarized array elements	4-8 dB
2 element helix	Use two element helix arrays, one right hand and one left hand, for use with respective satellite. The passive array may provide additional enhancement due to shielding of the active array.	3-6 dB
4 element helix	Not practical	-
2x5 element crossed slot	Use a dual polarized patch antenna element and a switchable hybrid.	3-6 dB
4 element horn and 2x4 element horn	Use rotating ¼ wave plate polarizers in front of each horn or use ortho feeds in each horn with hybrids.	3-6 dB

9.4.6 Conclusions

The best candidate from the standpoint of isolation is the four-element helix. However, all systems require some degree of isolation enhancement as illustrated in Section 9.4.5.

With minor enhancement, the horn arrays can be made to conform to the 20 dB isolation criteria. The crossed slot arrays can benefit most from illumination tapering combined with polarization diversity and it is likely that the full 20 dB isolation can be achieved.

The reflector antennas (the parabolic and the corner) and the two-element helix array pose the greatest problem for isolation. A combination of absorbing patches and polarization diversity for the parabolic reflector and helix array seems best. The corner reflector could best benefit from shielding techniques only.

As in the linear arrays, the planar arrays can benefit most from illumination taper. Using a dual polarized element would ensure 20 dB isolation for the conformal array candidate.

A final observation resulting from this study relates to all candidates with fixed elevations. When gain improvement is affected by elevation beam sharpening the isolation may be reduced for selected earth station locations. For instance, the 1x4 horn array has better isolation for Cape Flatters than the 2x4 horn array. Further note that the degradation is for satellite #1 only. The reason for this is apparent from Figure 9-3 where the Cape Flatters satellite pair are on a sloping line. While this places satellite #2 roughly on the peak of the beam, satellite #1 lies well off the peak effectively reducing isolation by 1-2 dB when communication with satellite #1 is desired.

A sample comparison of two candidate antennas, including isolation enhancement is summarized in Table 9-10.

TABLE 9-10
MINIMUM ISOLATION COMPARISON

Antenna	Uniform Illumination	Tschebysheff Illumination	Cross Polarization	Net Isolation Uniform	Net Isolation Tschebysheff
2x5 Crossed Slot	13.0dB	18.0dB (.2dB gain loss)	3.5 - 8dB	16.5 - 21dB	21.5 - 26.0dB
Ring	13.0dB	18.0dB (.2dB gain loss)	4.0 - 8dB	17 - 24dB	22.0 - 26.0dB

10.0 ANTENNAS SELECTED FOR FURTHER STUDY

After the initial study developed the costs and preliminary designs for nine antennas, two antennas were then selected for further studies. The selected antennas, based on performance, cost and weight/height, were the ring array and the linear array.

10.1 Ring Array

The ring array has the distinctions of low height, good elevation coverage, more than 20 dB isolation with two satellites, and has the capability of increased isolation using the Tschebyscheft amplitude distribution.

The 16-element ring array is shown in Figure 10-1. The ring array consists of 16 elements spaced around a 36-inch diameter ground plane. A stepper motor is used to position the beam in 16 positions every 22-1/2 degrees around the circle. This switching interval is not sufficiently fine to allow for good satellite isolation in the two-satellite case. Furthermore, a severe loss in gain occurs at the beam crossover levels. As a consequence, an additional provision is made to switch the beam in 7-1/2 degree steps electronically by means of phase shifters.

Figure 10-2 shows a schematic of the antenna where five elements are used at a time. A stepper motor is used to step the inner contactless commutator. The commutator is a one-quarter-wave series circuit in microstrip. The equivalent circuit in coaxial and microstrip is shown in Figure 10-3. The series impedance for center conductor and the ground plane will be 15 ohms. A curve of VSWR for an equivalent stripline circuit is shown in Figure 10-4. The mechanical details are shown in Figure 10-5. The noncontacting assembly is coated with .005 teflon to provide a low friction teflon bearing. The phase shifter will switch the appropriate line lengths into the antenna circuit by means of a reed switch which is actuated by means of TTL logic. RF reed switches have isolations of 40 dB and a contact resistance of less than 0.1 ohm. The vacuum-type reed switch is a high power switch capable of switching 50 watts peak power. The antenna gain is tabulated in Table 10-1 for the worst case gain at a 7-1/2 degree scan position.

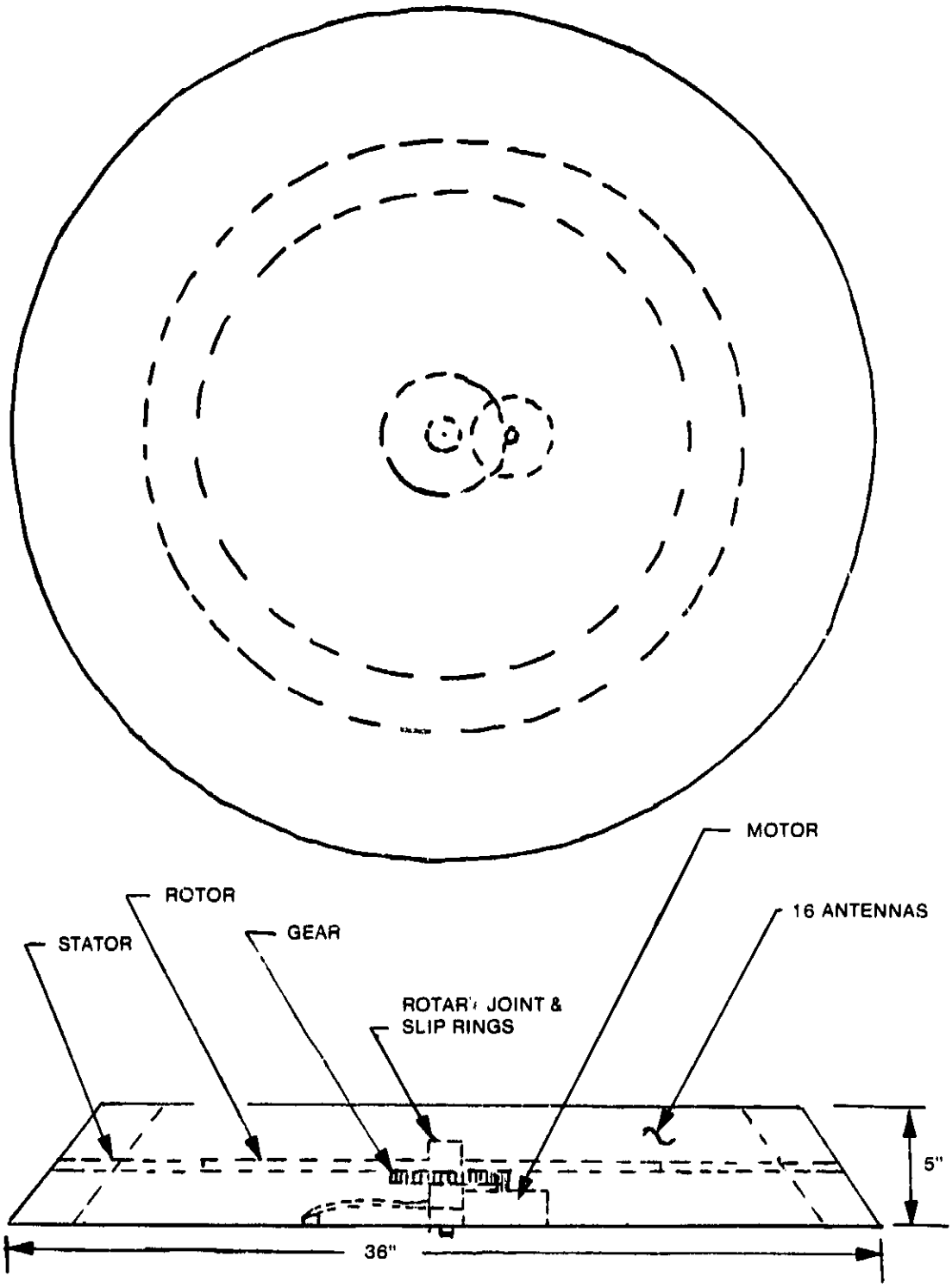


FIGURE 10-1. RING ARRAY

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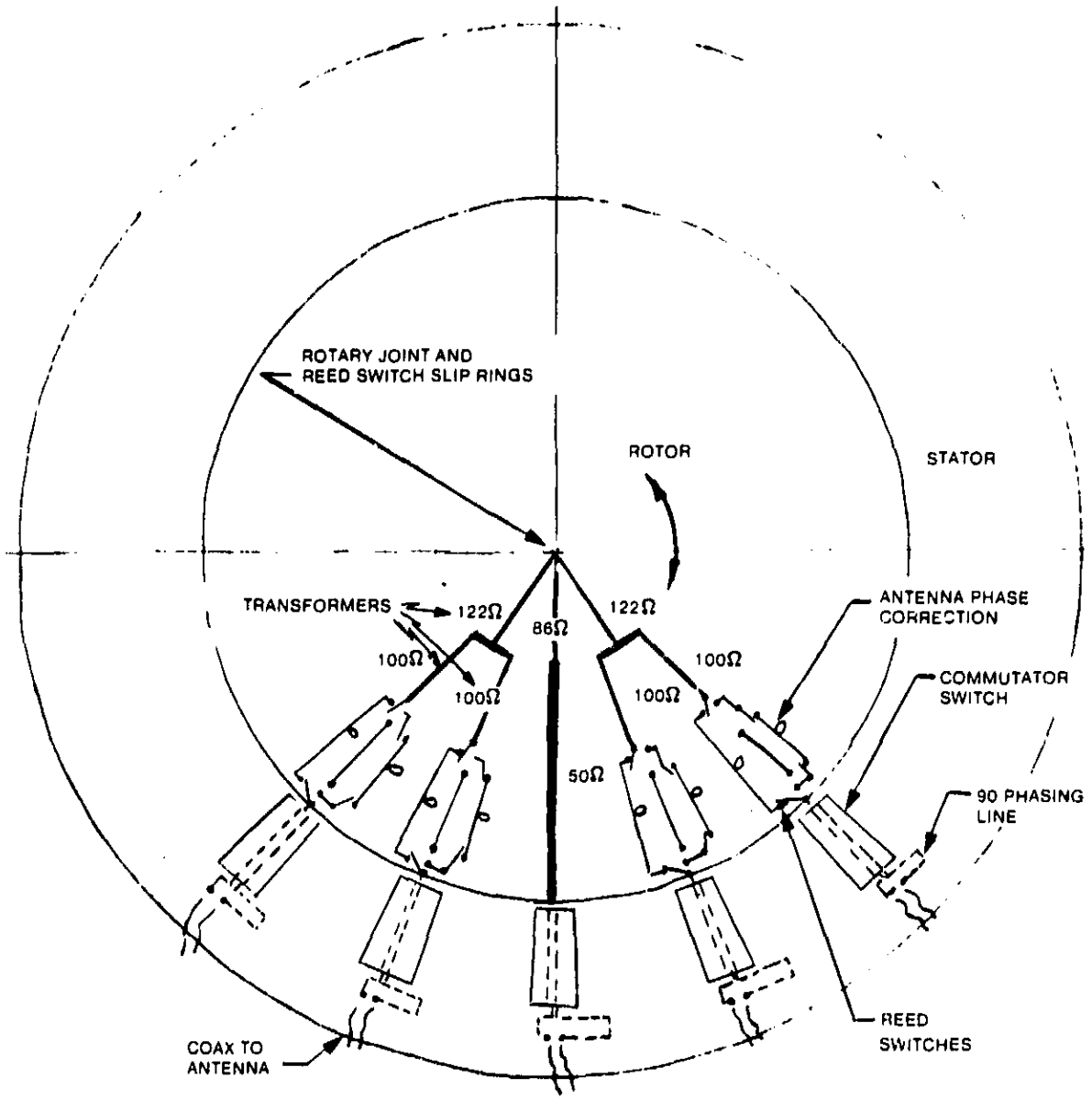


FIGURE 10-2. ANTENNA SCHEMATIC

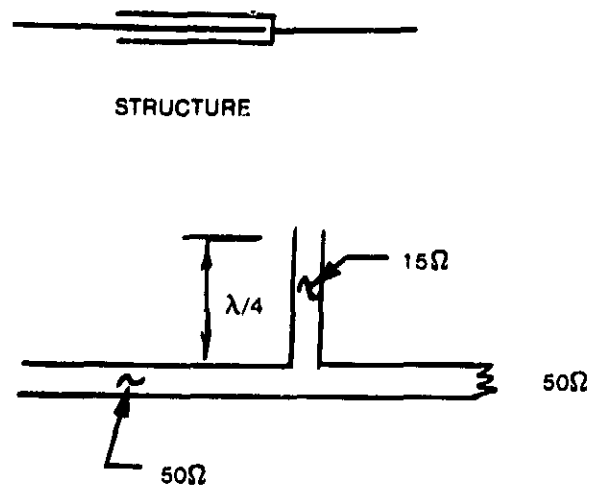


FIGURE 10-3. COMMUTATOR EQUIVALENT CIRCUIT

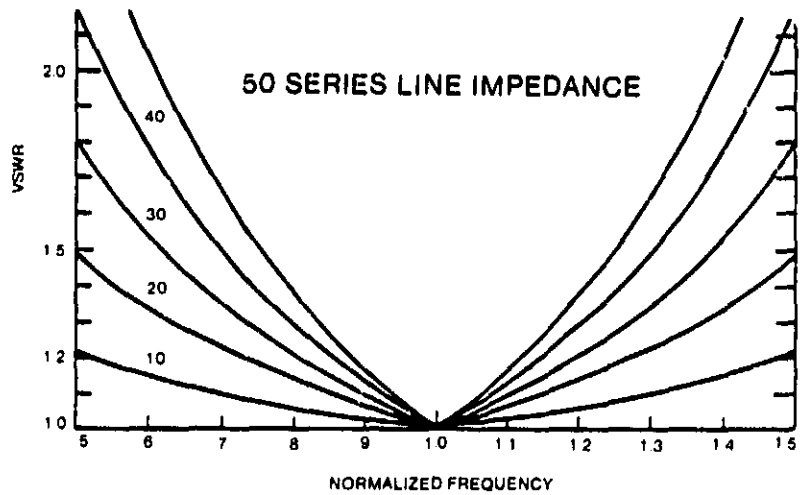


FIGURE 10-4. COMMUTATOR VSWR

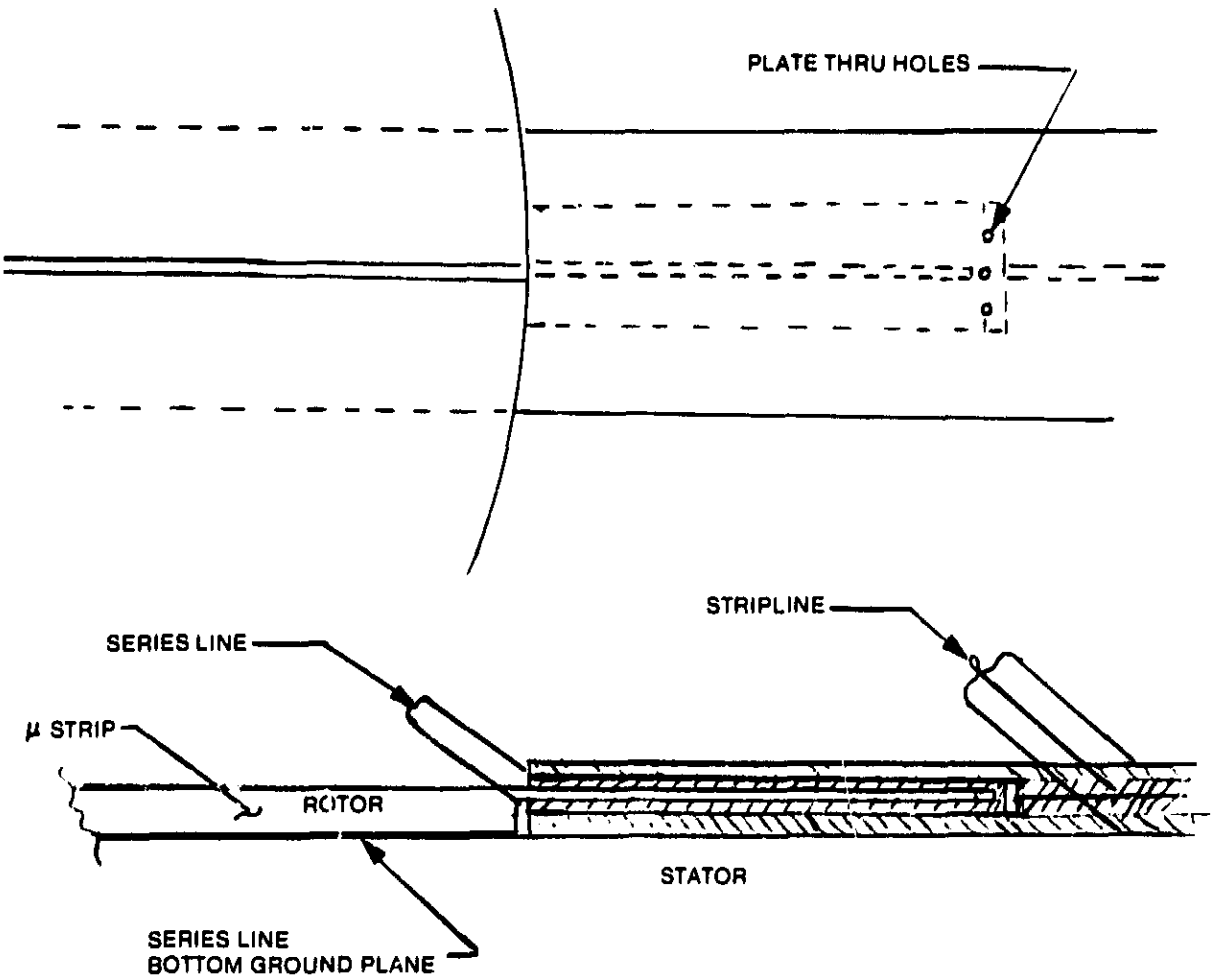


FIGURE 10-5. COMMUTATOR

Table 10-1 is a tabulation of antenna gain analysis for CONUS, ALASKA and the two-satellite case. Ground plane effects on the elevation pattern is shown in scale model measurements of Figure 10-6. The antenna is scanned up 20 degrees and located at the edge of the ground plane. The axial ratio is 3 dB maximum.

The scan loss in the azimuth plane occurs because the elements are displaced circularly, creating a non-linear phase front. Additional loss occurs because the elements main beam direction does not always lie in the direction of the arrays main beam. With scanning, the useful beam directions are offset ±7-1/2 degrees more from the beam maximum pointing direction. For the two-satellite case, an 18 dB Dolph-Tchebyscheff is used to provide maximum gain for a minimum sidelobe level. Assuming a land mobile antenna axial ratio of up to 4 dB and satellite antenna axial ratio of up to 1 db, an improvement in isolation of from 5-to-10 dB would be possible for all combinations of axial ratios. These axial ratios and the amplitude taper will provide an isolation of from 22-to-33 dB giving ample design margin.

The azimuth beamwidth is 28 degrees and the elevation beamwidth is 60 dB. The crossover loss is 0.9 dB.

Signal acquisition is accomplished by scanning in one direction until the maximum AGC level is reached, then stopping and going in the reverse direction until the AGC level is maximized for a beam position. As the car turns the AGC level will decrease (or possibly increase) until the AGC level drops 1 dB. The antenna will then switch electronically in one direction to see if the AGC increases. If the AGC increases, the antenna will be scanned in that direction if it decreases the antenna. The radiating element is a one-half wavelength square patch antenna on a one-inch thick air substrate.

10.2 2 x 5 Crossed Slot Array

The 2 x 5 crossed slot antenna array was selected for further study because it is low-cost, can provide the required antenna and satellite isolation with the ability to provide increased isolation margin using Dolph-Tschebyscheff amplitude distributions. The antenna is similar to the 1 x 5 linear array antenna previously discussed. However, arraying the antenna 2 x 5 as shown in Figure 8-2 will result in the ability

TABLE-10-1

RING ARRAY GAIN ANALYSIS

CONUS Coverage	
Directivity - 5 Element Linear Array (25 in. long)	6.5 dB
Element Factor	8.0 dB
Elevation Coverage Loss	-0.3 dB
Element Skew Loss Scanned to 7-1/2 Degrees	-0.6 dB
Phase Shifter Loss	-0.2 dB
Commutator Loss	-0.3 dB
Transmission Line Loss (.18 dB/ft.)	-0.4 dB
Mismatch Loss	-0.5 dB
Beam Crossover Loss	-0.9 dB
	11.3 dB
CONUS and ALASKA	
CONUS Gain	11.3 dB
Additional Elevation Coverage Loss	-2.0 dB
	9.3 dB
Two-Satellite Case CONUS	
CONUS Gain Uniform Amplitude distribution	11.3 dB
Loss due to 18 dB Sidelobe Dolph-Tchebyscheff taper	-0.2 dB
	11.1 dB
Two-Satellite Case CONUS and ALASKA	
ALASKA Gain Uniform Amplitude Distribution	9.3 dB
Loss due to 18 dB Sidelobe Dolph-Tchebyscheff	-0.2 dB
	9.1 dB

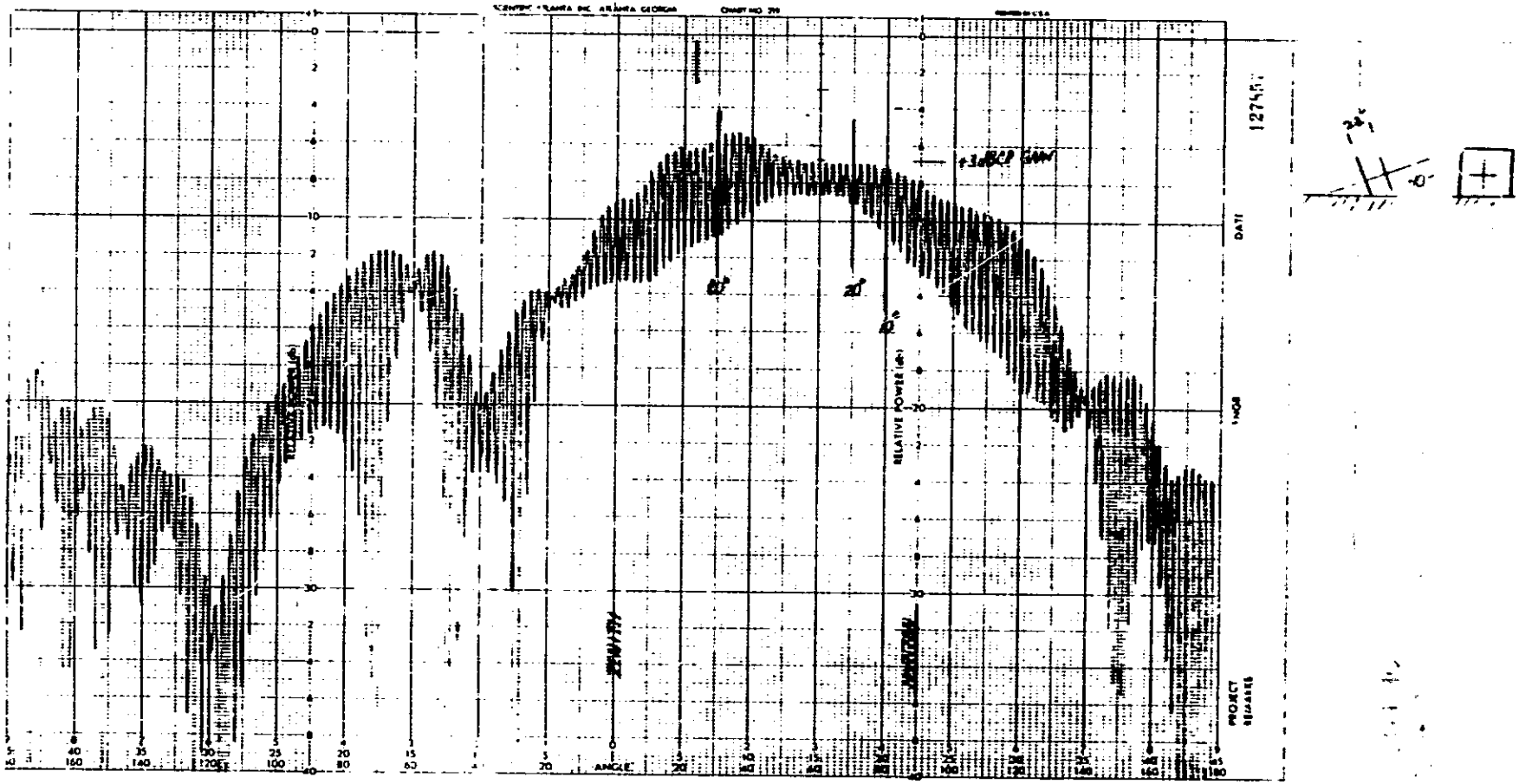


FIGURE 10-6. GROUND PLANE EFFECTS ON EDGE MOUNTED ANTENNA

to position the elevation beam maximum higher than the 20 degrees mandated by the ground plane. This is achieved by phasing the second linear array to provide a beam maximum at 40 degrees elevation. Unresolved issues with the antenna is the effect of pattern blockage of one linear array by the other. However, this blockage can potentially be reduced by elevations and reorienting the blocked antenna. The projected performance characteristics are summarized in Table 10.2-1.

TABLE 10.2-1

2 X 5 ARRAY PERFORMANCE

GAIN CONUS

ARRAY 5 ISOTROPIC ELEMENTS @ λ/2 SPACING+	+7	dBCP
ELEMENT GAIN	+5	dB
ARRAY TWO ELEMENTS IN ELEVATION	+3.0	dB
I^2R LOSS - SWITCH & PCB	-0.5	dB
VSWR LOSS 1.8:1	-0.35	dB
ELEVATION COVERAGE LOSS AT 60 DEGREES	-1.1	dB
MONOPULSE CROSSOVER LOSS	-1.0	dB
	+12.05	dB

GAIN ALASKA

ARRAY 5 ISOTROPIC ELEMENTS @ λ/2 SPACING	+7	dBCP
ELEMENT GAIN	+5	dB
ARRAY TWO ELEMENTS IN ELEVATION	+3	dB
I^2R LOSS	-0.5	dB
VSWR LOSS	-0.35	dB
ELEVATION COVERAGE LOSS AT 10 DEGREES	-4	dB
MONOPULSE CROSSOVER LOSS	-0.5	dB
	9.55	dB

11.0 COST RATIONALE

Cost of the nine antennas was estimated for 100 and 10,000 units. Reducing the cost of large quantities of production requires much time and thought. Methods of minimizing labor and materials need to be determined. Recent experience on moderate production quantities of 460 and 800 has shown the great advantage of using castings, injection molding, and compression molding techniques to reduce manufacturing labor. As a consequence the cost estimates were based on those manufacturing techniques. The per-unit labor price was estimated and a learning rate applied for the quantity involved. There is a 30 percent variance applied to the labor cost figure to account for losses during the production process. The dollar values are for 1983 dollars and do not include profit. Cost estimates were made from engineering sketches. As a result the estimated cost accuracy is $\pm$ 40 percent. The learning curve used is decreased in Appendix A. Estimated cost of the nine antennas is shown in Figure 11-1 for 100 units and Figure 11-2 for 10,000 units. Appendix B provides detailed cost data. The cost components for the major subassemblies are shown in Table 11-1 for selected cases. Major component cost for the conformal array is the phase shifters. For compass pointing systems add $250.00.

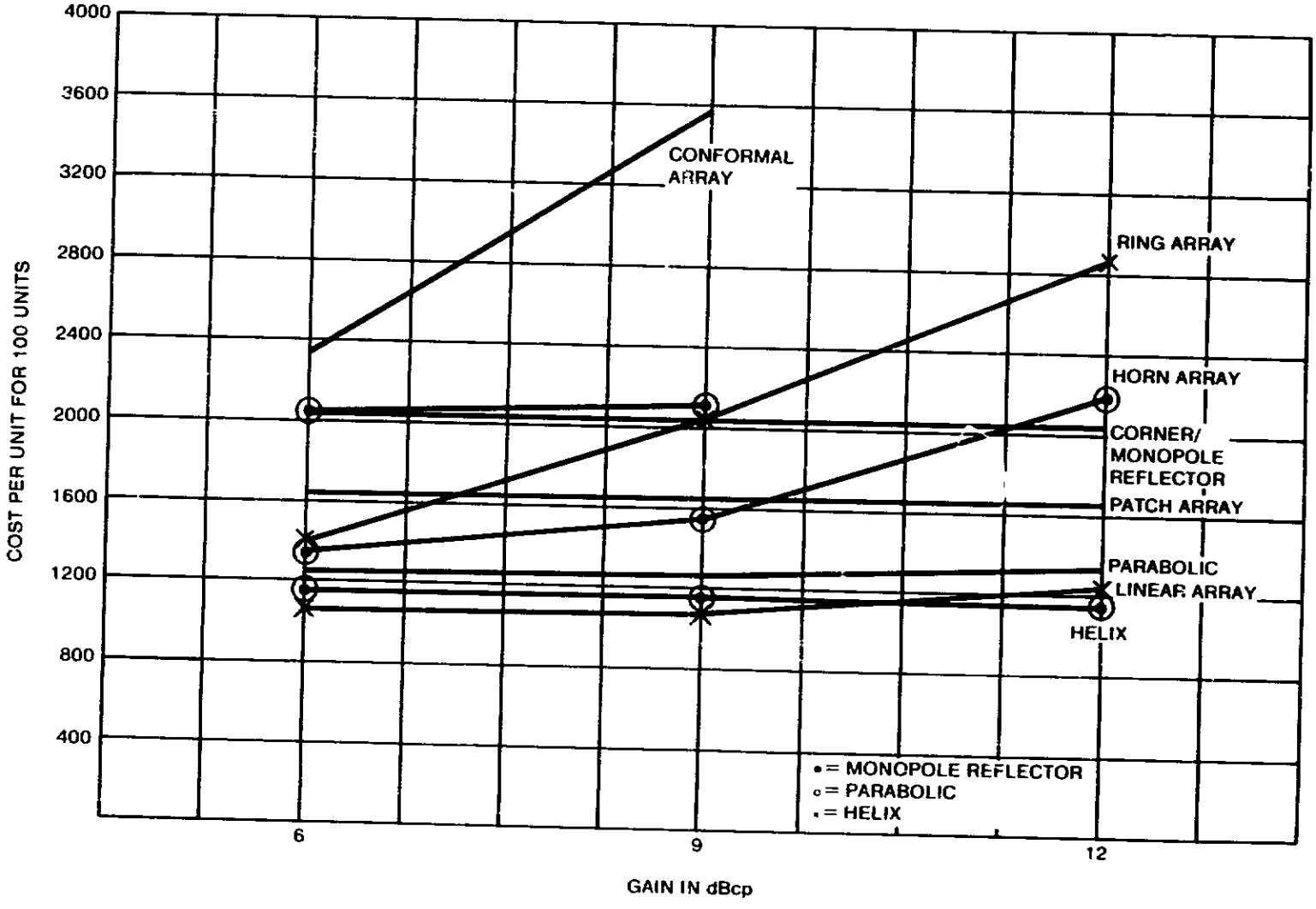


FIGURE 11-1. COST FOR 100 UNITS

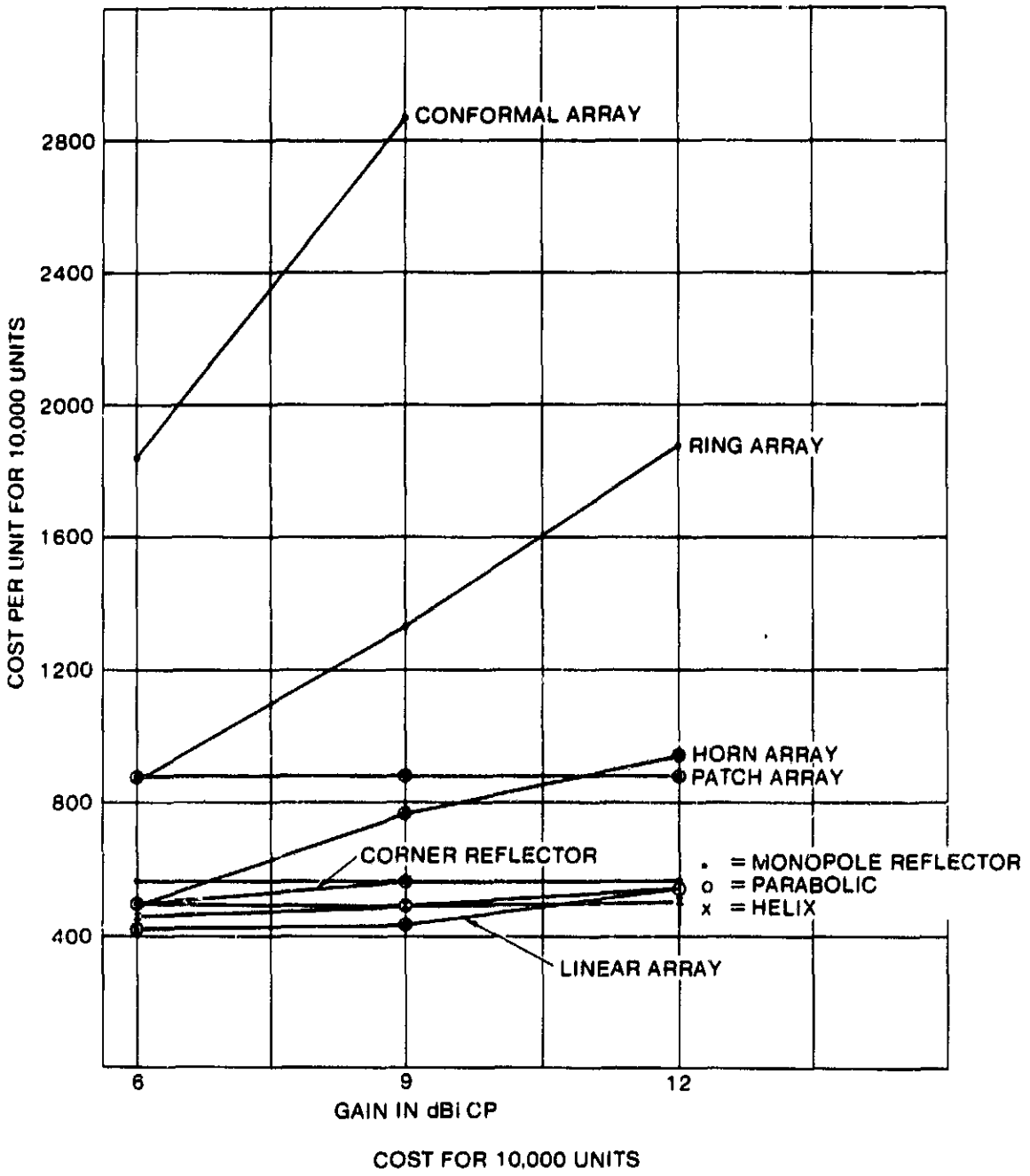


FIGURE 11-2. COST FOR 10,000 UNITS

TABLE 11-1

ONE UNIT COST OF MAJOR ANTENNA SUBASSEMBLIES

		LOT 100 ($)	LOT 10,000 ($)
1.	LINEAR ARRAY -12 dB GAIN		
	ANTENNA	865	443
	SERVO	202	52
	MOTOR DRIVE	145	42
2.	RING ARRAY		
	ANTENNA	2222	17.75
	SERVO	200	50
	MOTOR DRIVE	524	53
3.	CONFORMAL ARRAY - 9 dB		
	ANTENNA	780	607
	PHASE SHIFTERS	2600	2080
	ANTENNA CONTROL	320	180

12.0 BREADBOARD AND PROTOTYPE DEVELOPMENT

The effort required to build breadboard and prototype model ring arrays and 2 x 5 linear arrays was estimated. A breadboard is defined as a laboratory-built working model. A prototype is defined as a working model built to a set of manufacturing drawings. The effort includes building the arrays, radome, motor drive, and servo system. Complete testing will be performed to verify the performance of the antennas. A complete set of drawings will be made for the prototype. Tables 12-1 and 12-2 outline the price and schedule.

TABLE 12-1
BREADBOARD COST AND SCHEDULE

	COST	TIME
2 x 5 ARRAY	$200,000	12 MO
RING ARRAY	$300,000	12 MO

TABLE 12-2
PROTOTYPE COST AND SCHEDULE

	COST	TIME
2 x 5 ARRAY	$100,000	6 MO
RING ARRAY	$150,000	9 MO

APPENDIX A

LEARNING CURVE ANALYSIS FOR PRODUCTION QUOTES

APPENDIX A

Learning Curve Analysis for Production Quotes

1. Introductory Concepts:

1.1 Learning Curve

For production quantities of an item, the cost per item decreases as the number of items increases. The mathematical relationship between unit cost and number of units produced is called the learning curve for that item. It was found experimentally that the recursion equation between the unit cost of N^{th} and $2N^{th}$ units is

$$C_{2N} = KC_N \qquad \text{where } K \leq 1$$

The table below shows how the recusion equatio provides estimates of the unit cost of the N^{th} unit.

TABLE A-1

No. Units N	Cost Per Unit
1	C_1
2	KC_1
4	K^2C_1
8	K^3C_1
$N=2^n$	K^nC_1

if the cost of the N^{th} unit is C_N, then

$$C_N = K^nC_1 = C_1(K)^{\frac{\log N}{\log 2}} \qquad (1)$$

The above equation is the learning curve. C_1 is the 1^{st} unit cost, K is the learning curve improvement expressed as a decimal (for 90% learning curve, K = 0.90) and N is the number of units produced.

The learning curve is usually expressed graphically on log-log paper with a normalized 1st unit cost $C_1 = 1$. Hence equation (1) becomes

$$\log C_N = \frac{\log K}{\log 2} \log N \tag{2}$$

Thus, the learning curve is a straight line with slope $S = \frac{\log K}{\log 2}$ when plotted on log-log paper. Table A-2 gives the learning curve slope S for several percentages. The slope S + 1 of the cumulative cost curve is also given.

TABLE A-2

%	S	S + 1
95	-0.07401	0.92599
90	-0.15201	0.84799
80	-0.32193	0.67807
70	-0.51457	0.48543
60	-0.73697	0.26303

Also, by rearranging the log terms of equation (2) and taking the antilog, one obtains

$$C_N = C_1 (N)^{\frac{\log K}{\log 2}} \log N \tag{3}$$

As an alternate form for the learning curve, computation wise, equation (3) is more useful when greater accuracy is required than provided by graphical methods. A family of learning curves for up to 1,000 units is provided by Figure A-1. The graphical accuracy is estimated to be 2%. Overall accuracy is also dependent upon the assumed learning curve percentage. For example, the % error B in the learning curve factor

$$F = (K)^{\frac{\log K}{\log 2}} \text{ is}$$

$$B = 100 \frac{\log K}{\log 2} \frac{dK}{K} \tag{4}$$

For a 1% error in the learning curve (1% in 90% or $\frac{dK}{K} = 0.011$), E increases with log N and is 16.7% for N = 100, 10% for N = 1000, and is directly proportional to the assumed

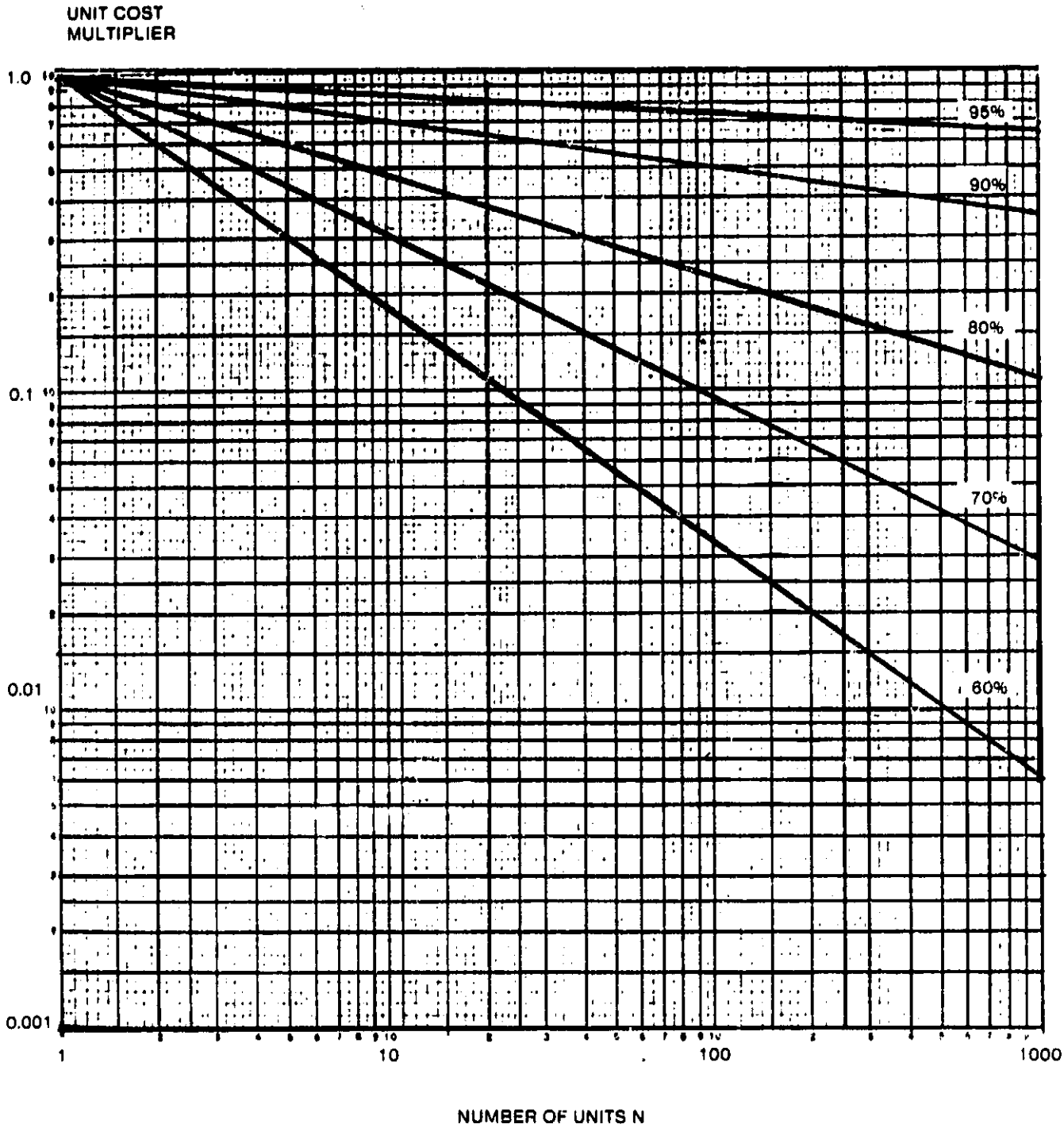


FIGURE A-1. LEARNING CURVE UNIT - COST MULTIPLIER

percentage error in K. Therefore unit cost accuracy is critically dependent upon the learning curve assumed.

1.2 Cumulative Cost

A second important concept is that of the cumulative cost of N units. The cumulative cost, the sum of the unit cost of N units, is expressed by

$$C_T = \sum_1^N C_1(K)^{\frac{\log N}{\log 2}} = \sum_1^N C_1(N)^{\frac{\log K}{\log 2}} \tag{5}$$

whereas the unit cost C_N is a relatively simple computation, the cumulative cost requires N sums and is most accurately expressed by a cumulative cost table. The format of a cumulative cost table is shown in Table 3 which provides the cumulative cost multiplier M in the main body as a function of N and the learning curve percent. A family of cumulative cost plots on log-log paper is shown in Figure A-2 for up to 1,000 units. Expressed logarithmically, the cumulative cost curve is a straight line for large N. Note, however, that for small N the curve has a variable slope. Therefore, an error in the curve will be made if it is plotted from a single point to the origin. An approximation to the cumulative cost curve is obtained by integrating the learning curve equation (3)

$$C_T = \int_0^N C_N \, dN = C_1 \int_0^N N^S \, dN = \frac{C_1 N^{S+1}}{S+1} \tag{6}$$

where S = slope of learning curve = $\frac{\log K}{\log 2}$

Again, it is desirable to normalize the curve by letting $C_T = C_1$ when N = 1, so that

$$C_T = C_1 N^{S+1} \tag{7}$$

Because the integration of equation 6 does not exactly represent the summation of equation 5, equation 7 is not accurate. This is seen by taking the log of both sides of equation 7. The slope of the log-log curve is S + 1, which is a constant independent of N, whereas Figure A-1 and Table A-3 clearly show the nonlinear slope of the cumulative cost curve for small N. Therefore curves plotted from equation 7 intersect

TABLE A-3
EXPERIENCE CURVE TABLES
CUMULATIVE VALUES

Unit	60%	65%	70%	74%	75%	80%	85%	90%	95%
1	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000	100.000
2	160.000	165.000	170.000	174.000	175.000	180.000	185.000	190.000	195.000
3	204.502	215.521	236.818	236.040	238.384	250.210	262.291	274.621	287.192
4	240.502	257.771	275.518	280.809	294.634	314.210	334.541	355.821	377.142
5	271.043	294.550	310.503	340.810	345.908	373.784	103.109	433.920	466.214
6	297.744	327.380	359.275	388.427	393.446	429.942	468.800	510.079	553.796
7	321.578	357.228	356.015	429.369	428.037	483.391	532.172	584.474	640.123
8	313.178	384.690	480.315	489.882	480.225	534.591	593.585	654.374	726.123
9	362.___	410.214	452.598	508.393	520.400	583.886	663.324	728.980	811.116
10	381.306	404.101	403.177	545.172	558.856	631.537	711.666	799.449	893.450
11	398.368	458.___	502.__3	669.___	___.	677.748	768.690	868.904	979.190
12	414.409	477.___	559.181	___.___	684.173	722.063	624.440	937.447	1,062.393
13	429.512	498.307	576.891	647.854	800.852	766.174	879.248	1,005.161	1,445.105
14	443.812	517.702	602.560	679.032	690.405	809.234	933.109	1,072.116	1,227.365
15	437.408	556.208	627.300	709.371	731.005	851.054	986.106	1,138.373	1,309.205
16	470.363	554.184	661.400	739.857	783.545	892.014	1,038.306	1,302.983	1,390.656
17	482.757	571.324	575.672	760.065	784.400	933.182	1,089.770	1,268.991	1,471.742
18	484.639	587.915	607.270	797.556	884.581	971.618	1,140.549	1,333.437	1,552.486
19	508.058	603.957	719.248	825.285	853.993	1,010.374	1,190.888	1,397.355	1,632.907
20	517.052	619.596	740.654	852.601	882.835	1,048.495	1,240.2228	1,460.777	1,713.025
21	527.659	634.571	761.520	879.217	941.099	1,086.021	1,289.204	1,523.730	1,792.852
22	537.908	649.217	781.910	805.359	938.822	1,122.990	1,337.649	2,586.240	1,872.405
23	547.827	663.463	801.830	830.972	966.089	1,159.434	1,385.592	1,648.329	1,951.698
24	557.439	677.338	621.318	956.116	992.779	1,195.382	1,433.058	1,710.017	2,030.741
25	566.766	690.804	840.402	980.818	1,019.070	1,230.860	1,480.073	1,771.324	2,109.545
26	575.828	704.065	859.104	1,005.103	1,044.936	1,265.893	1,526.657	1,832.266	2,188.122
27	584.641	716.961	877.447	1,028.993	1,070.400	1,300.503	1,572.830	1,892.860	2,266.479
28	593.222	729.567	895.449	1,052.508	1,095.483	1,334.711	1,618.612	1,953.120	2,344.625
29	601.583	741.902	913.129	1,075.667	1,120.203	1,368.584	1,664.019	2,013.059	2,429.569
30	609.737	753.980	930.504	1,098.488	1,144.578	1,401.990	1,401.066	2,072.690	2,500.317
31	617.698	705.814	947.588	1,120.987	1,168.623	1,435.094	1,753.768	2,132.025	2,577.878
32	625.474	777.417	984.395	1,143.177	1,192.353	1,467.862	1,798.138	2,191.074	2,655.256
33	633.075	788.800	980.938	1,165.072	1,215.782	1,500.307	1,842.190	2,249.847	2,732.458
34	640.511	799.974	997.228	1,186,685	1,238.991	1,532.442	1,885.934	2,308.354	2,809.489

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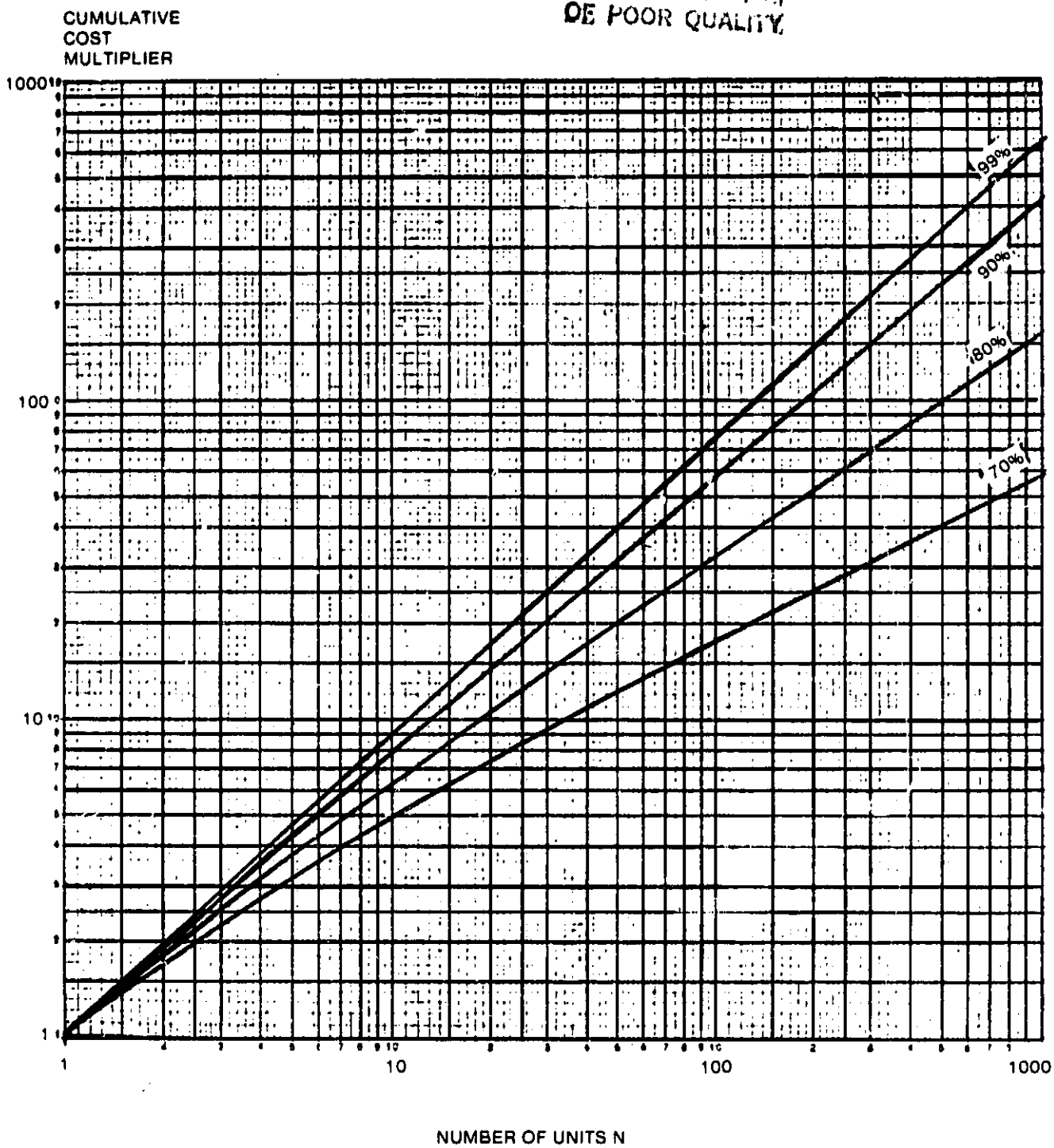


FIGURE A-2. VALUE OF THE CUMULATIVE COST MULTIPLIER

the origin, have the same slope as, but lie below the corresponding curves plotted for cumulative cost tables.

Use of equation 7 for cumulative cost estimates is not recommended. If more than 2% accuracy is required, a bound cumulative cost table for values of N up to 5,000 has been computed and should be used. As in the case of the unit cost estimates, the cumulative cost multiplier is critically dependent upon the assumed learning curve percentage. For example, if N = 1000, a 1% uncertainty in the assumed learning curve per cent results in from a 11.4% error for the 90% curve to a 18.6% error for the 60% curve in the cumulative cost multiplier.

1.3 Average Unit Cost

A third parameter of interest in the cost per unit averaged over a production run of N units. Equation 8 below provides the relationship between C_T (the cumulative cost) and C_{ave}, the average unit cost.

$$C_{ave} = \frac{C_T}{N} = \frac{C_1}{N} \Sigma (N)^S$$

In closed form, based upon equation 7,

$$C_{ave} = C_N N^S$$

Again, this equation is an approximation. For accurate results, the cumulative cost determined from tables should be divided by N to obtain C_{ave}.

USE OF LEARNING CURVE TABLES

Before using the tables, one must decide the number of units N to be produced, the cost of the first unit C_1 and the learning curve improvement K. K is a percentage which expresses the per unit cost reduction when the lot size is doubled. To use the tables, look up the row with the desired number of units N. Select the column with the correct learning curve percent K. Read off the learning curve multiplier F, and the cumulative cost multiplier M. The unit cost C_N the N^{th} unit is the product of the cost of the first unit C_1 and the multiplier F: i.e.

$$C_N = C_1 \times F$$

The cumulative cost C_1 of the entire run of N units is the product of the cost of the first unit and the multiplier M: i.e.,

$$C_t = C_1 \times M$$

The average cost C_A per unit for the entire run is the cumulative or total cost divided by the number of units in the run: i.e.

$$C_A = \frac{C_t}{N}$$

EXAMPLE #1: Computing N__ Unit, Lot Cumulative and Lot Average Costs

If N were 500 units, K equal to 90%, and the first unit cost $100, then in the N = 500 row of the table under the K 90 column, read off F = (1.38882 and M = 268.785. The unit cost of the 500^{th} unit is

$$C_{500} = 0.882 \times \$100 = 88.8882$$

The cumulative cost of total 500 units is

$$C_t = 225.785 \times \$100 = \$2287850$$

The average unit cost is

$$C_A = \frac{\$22,878.50}{500} = \$45.757$$

EXAMPLE #2: Extending Cost Estimates From Small to Large Lots

Assume a small lot N has been produced at a total cost C_t. Using the value for the learning curve percent K, look up the cumulative multiplier M corresponding to N. Compute the unit cost $C_1 = \frac{C_t}{M}$. For example N = 10, K = 90% and C_t = \$50,000. From the tables M = 7.999447 for N = 10 and K = 90. The $C_1 = \frac{50,000}{7.99447}$ = \$6,254.32. Having C_1 follow example 1 to obtain cost estimates for larger lot sizes.

EXAMPLE #3: Determinig Lot Costs in a Continuing Production Plan

Assume 100 units are to be produced, and the total cost of a lot 20 units. No's: 41-60, is desired. The lot cost is $C_L = C_1 (M_{60} - M_{40})$.

Assume K = 90% and C_1 = \$100, from the tables M_{60} = 37.5740 and M_{40} = 26,5427. Hence C_L = \$100 x (37,5740 - 26,5427) = \$1103.10.

APPENDIX B

DETAILED COST DATA

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CF-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT & AVERAGE HOURS
1	6 dB SLOTTED	100									
	LINEAR ARRAY										
	FAB. DETAIL PARTS				5.59		91.81		203.32	300.72	12030
	PCB		235								
	CABLE		175								
	CONNECTORS		900								
	MODULATOR DIODE		250								
	RADOME			3500							
	TOOLING RADOME			25000							
	ROTARY JOINT			10000							
	PCB FAB			7300							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		300								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		38660	46000							23230

TOTAL # 107890

TOTAL EACH # 1079

CF 11-16-4G

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT & AVERAGE HOURS
2	6 dB SLOTTED	10000									
	LINEAR ARRAY										
	FAB. DETAIL PARTS				440.31		730939		16 428.17	84,37181	975115
	PCB		23500								
	CABLE		17500								
	CONNECTORS		9 000								
	MODULATOR DIODE		20 000								
	RADOME			300000							
	TOOLING RADOME			25000							
	ROTARY JOINT			750000							
	PCB FAB			650000							
	MOTOR		400 000								
	SERVO AMP		300 000								
	BELT		7500								
	SHAFT		10000								
	BEARING LOWER		10006								
	UPPER		2500								
	BASE SUPPORT		20 000								
	MTG HARDWARE		10 000								
	ASSY & TEST									13250	530000
	TOTAL		1.030.000	1.725.000							1,505,115

TOTAL $4260.115

TOTAL EACH $426

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT & AVERAGE HOURS
3	9 dB SLOTTED	100									
	LINEAR ARRAY										
	FAB. DETAIL PARTS				539		91.81		203.32	900.72	12630
	PCB		479								
	CABLE		175								
	CONNECTORS		900								
	MODULATOR DIODE		250								
	RADOME			3500							
	TOOLING RADOME			2500							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	MOTOR		12700								
	SERVO AMP		30000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									290	1200
	TOTAL		38875	46000							23230

CF 11-16-46

TOTAL # 108125

TOTAL EA # 1081

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (MH-E)	UNIT # AVERAGE HOURS
4	9 dB SLOTTED	10 000									
	LINEAR ARRAY										
	FAB. DETAIL PARTS				440.31		750939		16428.11	24377.81	975115
	PCB		47 000								
	CABLE		17 500								
	CONNECTORS		9 000								
	MODULATOR DIODE		20 000								
	RADOME			350 000							
	TOOLING RADOME			25 000							
	ROTARY JOINT			750 000							
	PCB FAB			650 000							
	MOTOR		400 000								
	SERVO AMP		500 000								
	BELT		7 500								
	SHAFT		10 000								
	BEARING LOWER		10 000								
	UPPER		2 500								
	BASE SUPPORT		20 000								
	MTG HARDWARE		10 000								
	ASSY & TEST									1325D	530.000
	TOTAL		1 053 500	1775000							1505115

TOTAL # 4333.615

TOTAL EACH # 433

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ HQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (MH-E)	UNIT $ AVERAGE HOURS
5	12 dB SLOTTED	100									
	LINEAR ARRAY										
	FAB. DETAIL PARTS				10.99		182.03		396.6	589.42	23577
	PCB		958								
	CABLE		350								
	CONNECTORS		1806								
	MODULATOR DIODE		250								
	RADOME			3500							
	TOOLING RADOME			25000							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		900								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		40458	46000							34717

TOTAL $ 121175

TOTAL EA $ 1212

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT / AVERAGE HOURS
6	12 dB SLOTTED	10000									
	LINEAR ARRAY										
	FAB. DETAIL PARTS				87081		149791		38455.15	418305.1	1432206
	PCB		95800								
	CABLE		35000								
	CONNECTORS		18,000								
	MODULATOR DEV.		20,000								
	RADOME			350 000							
	TOOLING RADOME			25000							
	ROTARY JOINT			750 000							
	PCB FAB			650 000							
	MOTOR		400 000								
	SERVO AMP		300 000								
	BELT		7500								
	SHAFT		10 000								
	BEARING LOWER		10 000								
	UPPER		2 500								
	BASE SUPPORT		20 000								
	MTG HARDWARE		10 000								
	ASSY & TEST									13250	530000
	TOTAL		1128800	1775000							2462206

TOTAL $5366006
TOTAL EA $537

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (MHES)	UNIT AVERAGE HOURS
7	6 dB HELIX	100									
	ANTENNA										
	FAB DETAIL PARTS				37.70				330.93	26863	14745
	PCB		235								
	CABLE		350								
	CONNECTORS		1800								
	MODULATOR DIODE		2.50								
	RADOME			3500							
	RADOME TOOLING			25000							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING UPPER		500								
	LOWER		800								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		39735	46000							25945

TOTAL # 116800

TOTAL EA # 1168

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT AVERAGE HOURS
8	6 dB HELIX	10000									
	ANTENNA										
	FAB DETAIL PARTS				2926.04				26906.3	29832.34	1193.294
	PCB		92500								
	CABLE		35000								
	CONNECTORS		180000								
	MODULATOR DIODE		20000								
	RADOME			360 000							
	RADOME TOOLING			25 000							
	ROTARY JOINT			750 000							
	PCB FAB			650 000							
	MOTOR		400 000								
	SERVO AMP		300 000								
	BELT		7500								
	SHAFT		10 000								
	BEARING UPPER		8500								
	LOWER		10 000								
	BASE SUPPORT		20 000								
	MTG HARDWARE		10000								
	ASSY. & TEST									1329	530.00
	TOTAL		1218500	1725000							1723.294

TOTAL 4666794

TOTAL EA 467

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-24/SCC-24 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT & AVERAGE HOURS
9	9 dB HELIX	100									
	ANTENNA										
	FAB DETAIL PARTS				317				34453	38423	15369
	PCB		437								
	CABLE		700								
	CONNECTORS		3000								
	MODULATOR DIODE		250								
	RADOME			3500							
	RADOME TOOLING			25000							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	MOTOR		12100								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING UPPER		500								
	LOWER		900								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST										
										280	11200
	TOTAL		41487	46000							26569

TOTAL $ 114056

TOTAL EA $ 1141

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT AVERAGE HOURS
10	9 dB HELIX	10000									
	ANTENNA										
	FAB DETAIL PARTS				2926.4				2197.91	5123.98	1244.98
	PCB		43700								
	CABLE		70000								
	CONNECTORS		300000								
	MODULATOR DIODE		20000								
	RADOME			300000							
	RADOME TOOLING			25000							
	ROTARY JOINT			750000							
	PCB FAB			650000							
	MOTOR		400000								
	SERVO AMP		500000								
	BELT		7500								
	SHAFT		10000								
	BEARING UPPER		25000								
	LOWER		15000								
	BASE SUPPORT		90000								
	MTG HARDWARE		10000								
	ASSY & TEST									12350	530000
	TOTAL		1407200	1725000							1774948

TOTAL 4907158
TOTAL EA 491

CF 11-16-45

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT # AVERAGE HOURS
11	12 dB HELIX	100									
	ANTENNA										
	FAB DETAIL PRTS				37.70				373.83	411.53	164.61
	PCB		437								
	CABLE		1050								
	CONNECTORS		3600								
	MODULATOR DIODE		250								
	RADOME			3500							
	RADOME TOOLING			35000							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	MOTOR		12700								
	SERVO AMP		30000								
	BELT		160								
	SHAFT		1000								
	BEARING UPPER		500								
	LOWER		800								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		42437	46000							27661

TOTAL # 116098

TOTAL EA # 1161

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT AVERAGE HOURS
12	12 dB HELIX	10000									
	ANTENNA										
	FAB DETAIL PARTS				292604				3048827	333842	335370
	PCB		43700								
	CABLE		105000								
	CONNECTORS		360000								
	MODULATOR DIODE		20000								
	RADOME			300000							
	RADOME TOOLING			25000							
	ROTARY JOINT			750000							
	PCB FAB			650000							
	MOTOR		400000								
	SERVO AMP		500000								
	BELT		7500								
	SHAFT		10000								
	BEARING UPPER		25000								
	LOWER		10000								
	BASE SUPPORT		90000								
	MTG HARDWARE		10000								
	ASSY & TEST									1235D	530000
	TOTAL		1511.200	1725000							1865370

TOTAL $ 5101570

TOTAL EA $510

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
13	6&9 dB PARABOLIC	100									
	FAB DETAIL PARTS				36.13		83.49		327.13	436.75	17470
	PCB		235								
	CABLE		175								
	CONNECTORS		900								
	MODULATOR DIODE		250								
	RADOME			3500							
	RADOME TOOLING			25000							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	REFLECTOR TOOL			6000							
	REFLECTOR			2000							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING UPPER		500								
	LOWER		800								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY/TEST									280	11200
	TOTAL		38660	54000							28670

TOTAL $121330

TOTAL EA $1213

CF 11-16-4

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
14	6&9 dB PARABOLIC	10000									
	FAB DETAIL PARTS				1945.52		6820.58		26736.26	35502.36	1420094
	PCB		23500								
	CABLE		17500								
	CONNECTORS		9000								
	MODULATOR DIODE		20.000								
	RADOME			300000							
	RADOME TOOLING			95000							
	ROTARY JOINT			750000							
	PCB FAB			650000							
	REFLECTOR TOOL			6000							
	REFLECTOR			150000							
	MOTOR		400000								
	SERVO AMP		500000								
	BELT		7500								
	SHAFT		10000								
	BEARING UPPER		2500								
	LOWER		10000								
	BASE SUPPORT		20000								
	MTG HARDWARE		10000								
	ASSY/TEST									13250	530.00
	TOTAL		1030000	1881000							1950094

CF 11-16-4

TOTAL $4861094

TOTAL EA $486

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
14	12 dB PARABOLIC	100									
	FAB DETAIL PARTS				26.13	132.49			371.13	535.75	21430
	PCB		235								
	CABLE		175								
	CONNECTORS		900								
	MODULATOR DIODE		250								
	RADOME			3500							
	RADOME TOOLING			25000							
	ROTARY JOINT			10000							
	PCB FAB			7500							
	REFLECTOR TOOL			6000							
	REFLECTOR			8100							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT 30a		3000								
	BRAKING UPPER 30a		1500								
	LOWER		800								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY/TEST									280	1120
	ELEVATION MOTOR		3500								32630
	TOTAL		41560	54100							

TOTAL $ 131890

TOTAL EA $ 1319

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ INQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
15	12 dB PARABOLIC	10000									
	FAB DETAIL PARTS				1945.62		9830.53		29736.11	41502.46	1160.02
	PCB		23500								
	CABLE		17500								
	CONNECTORS		9000								
	MODULATOR DIODE		20000								
	RADOME			300 000							
	RADOME TOOLING			25000							
	ROTARY JOINT			750 000							
	PCB FAB			650 000							
	REFLECTOR TOOL			6000							
	REFLECTOR			160 000							
	MOTOR		400 000								
	SERVO AMP		500 000								
	BELT		7500								
	SHAFT 3ea		30 000								
	BEARING UPPER	3ea	7500								
	DOME		10 000								
	BASE SUPPORT		20000								
	MTG HARDWARE		10 000								
	ASSY/TEST									13250	530.00
	ELEVATION MOTOR		300 000								
	TOTAL		1355000	1891 000							2190.02

TOTAL $ 5436.04

TOTAL EN 544

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
17	6 dB HORN ARRAY	100									
	FAB DETAILS				43.29		91.81		515.66	650.76	26030
	HORN TOOLING			3500							
	HORN 2ea			7500							
	RADOME			3500							
	RADOME TOOLING			25000							
	COAX		525								
	CONNECTORS		900								
	PCB		935								
	PCB FAB			7500							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	MODULATOR DIODE		2500								
	ROTARY JOINT			10000							
	TOTAL		41260	57000							37230

TOTAL 135490

TOTAL EA 1355

CF 11-16-4G

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-23/SCC-23 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
18	6 dB HORN ARRAY	10000									
	FAB DETAILS				3366.39		7509.39		4252.11	53599.11	2.13599
	HORN TOOLING			3500							
	HORN 2pc			700000							
	RADOME			300 000							
	RADOME TOOLING			25 000							
	COAX		52500								
	CONNECTORS		9000								
	PCB		23500								
	PCB FAB			650000							
	MOTOR		400 000								
	SERVO AMP		300 000								
	BELT		7500								
	SHAFT		10 000								
	BEARING LOWER		10000								
	UPPER		2500								
	BASE SUPPORT		20 000								
	MTG HARDWARE		10 000							13250	530000
	ASSY & TEST										
	MODULATOR DIODE		20000								
	ROTARY JOINT			750,000							
	TOTAL		1065000	2428500							743599

CF 11-16-

OF POOR QUALITY

TOTAL 4237099

TOTAL EA 424

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
19	9 dB HORN ARRAY	100									
	FAB DETAILS				43.29		91.81		873.55	1008.65	40346
	HORN TOOLING			4500							
	HORN 2 pcs			11000							
	RADOME			3500							
	RADOME TOOLING			25000							
	COAX		875								
	CONNECTORS		1350								
	PCB		470								
	PCB FAB			7500							
	MODULATOR DIODE		2500								
	ROTARY JOINT			10000							
	MOTOR		12700								
	SERVO AMP		30000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		300								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASST & TEST									280	11200
	TOTAL		41295	60500							51546

CF 11-16-

TOTAL # 154341

TOTAL EA # 1543

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
20	9 dB HORN ARRAY	10 000									
	FAB DETAILS				3366.29		7509.39		72155.59	83031.27	332.1250
	HORN TOOLING			4500							
	HORN 2 PCS			900 000							
	RADOME			300 000							
	RADOME TOOLING			85000							
	COAX		87500								
	CONNECTORS		135000								
	PCB		47000								
	PCB FAB			630 000							
	MODULATOR DIODE		26000								
	ROTARY JOINT			750 000							
	MOTOR		400 000								
	SERVO AMP		500 000								
	BELT		7500								
	SHAFT		10 000								
	BEARING LOWER		10 000								
	UPPER		2.500								
	BASE SUPPORT		90 000								
	MTG HARDWARE		10 000								
	ASSY & TEST									1250	530.000
	TOTAL		1249500	3629500							3.851.250

TOTAL $ 7730250

TOTAL EA. 773

CF 11-16-4

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
21	12 dB HORN ARRAY	10000									
	FAB DETAILS				336.29		7509.39		1335.64	14382.45	5715296
	HORN TOOLING			4500							
	HORN 4 Pcs			40 0000							
	RADOME			40 0000							
	RADOME TOOLING			25000							
	COAX		175000								
	CONNECTORS		270000								
	PCB		67000								
	PCB FAB			7500							
	MODULATOR DIODE		20000								
	ROTARY JOINT			750000							
	MOTOR		400 000								
	SERVO AMP		500 000								
	BELT		7500								
	SHAFT		10 000								
	BEARING LOWER		10 000								
	UPPER		2500								
	BASE SUPPORT		9000								
	MTG HARDWARE		10000								
	ASSY & TEST									132.50	530.00
	BEAM SLOUCH COMPENSATION	EA	5000								
	TOTAL		1542000	1587000							6305.216

TOTAL 9434296

TOTAL EA 943

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
32	12dB HORN ARRAY	100									
	FAB DETAILS				43.29		91.81		164.55	174965	69986
	HORN TOOLING			4500							
	HORN 4 pair			40000							
	RADOME			4000							
	RADOME TOOLING			25000							
	COAX		1750								
	CONNECTORS		2700								
	PCB		670								
	PCB FAB			7500							
	MODULATOR DIODE		2500								
	ROTARY JOINT			10000							
	MOTOR		13700								
	SERVO AMP		90000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	BEAM SWITCH COMPONENTS		600								
	TOTAL		45320	91000							81186

TOTAL $ 217506

TOTAL EA $ 2175

CF 11-16-

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-24/SCC-24 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
23	FAB MONOPOLE REF.	100									
	FAB DETAIL PARTS				29.38		83.49		439.35	552.22	22089
	RADOME TOOL OUTER			25000							
	RADOME TOOL INNER			25000							
	RADOME TOOL INSIDE			25000							
	RADOME FAB 3pc			9000							
	CORRUGATION TOOL			25000							
	CORRUGATION FAB			10000							
	PCB		235								
	PCB FAB			7500							
	CONNECTOR		150								
	MODULATOR DIODE		2500								
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY/TEST									280	11200
	ROTARY JOINT			10000							
	TOTAL		39985	136500							33289

TOTAL $ 200174

TOTAL EA $ 2008

CF 11-16-86

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT $
24	69.12 dB MONOPOLE REF.	10000									
	FAB DETAIL PARTS				2312.31		6820.58		36023.18	45136.07	1805443
	RADOME TOOL OUTER			25000							
	RADOME TOOL INNER			25000							
	RADOME TOOL INSIDE			25000							
	RADOME FAB 3ea.			7500							
	CORRUGATION TOOL			25000							
	CORRUGATION FAB			150000							
	PCB		235								
	PCB FAB			250000							
	CONNECTOR		15000								
	MODULATOR DIODE		20000								
	MOTOR		400000								
	SERVO AMP		500000								
	BELT		7500								
	SHAFT		10000								
	BEARING LOWER		10000								
	UPPER		2500								
	BASE SUPPORT		20000								
	MTG HARDWARE		10000								
	ASSY/TEST									13250	530000
	ROTARY JOINT			750000							
	TOTAL		995235	2257500							9335443

TOTAL # 5588178

TOTAL EA # 558

CF 11-16-4G

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT
23	6 dB CORNER REFLECT	100									
	FAB DETAIL PARTS				44.59				2829	325.49	13020
	RADOME TOOL OUTER			25000							
	RADOME TOOL INNER			25000							
	RADOME TOOL INSIDE			25000							
	RADOME FAB 3 ea.			9000							
	CORRUGATION TOOL			25000							
	CORRUGATION FAB			10000							
	PCB		235								
	PCB FAB			750							
	CONNECTOR		150								
	ROTARY JOINT			10000							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		900								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		39985	136500							24220

TOTAL $ 200705

TOTAL EA $2007

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ HQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-24/SCC-24 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT
26	6dB CORNER REFLECT	10000									
	FAB DETAIL PARTS				3594.18				2299212	26545.1	106804
	RADOME TOOL OUTER			25000							
	RADOME TOOL INNER			25000							
	RADOME TOOL INSIDE			25000							
	RADOME FAB 3ea.			7500							
	CORRUGATION TOOL			25000							
	CORRUGATION FAB			750 000							
	PCB		23500								
	PCB FAB			650 000							
	CONNECTOR		15000								
	ROTARY JOINT			750 000							
	MOTOR		400 000								
	SERVO AMP		500 000								
	BELT		7500								
	SHAFT		10 000								
	BEARING LOWER		10 000								
	UPPER		2500								
	BASE SUPPORT		20 000								
	MTG HARDWARE		15 000								
	ASSY & TEST									13250	530 000
	TOTAL		1018500	2257500							1591804

TOTAL $ 4867804

TOTAL EA $ 487

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-24/SCC-24 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT
27	9 dB CORNER REFLECT	100									
	FAB DETAIL PARTS				87.49				446.00	533.49	21334
	RADOME TOOL OUTER			25000							
	RADOME TOOL INNER			25000							
	RADOME TOOL INSIDE			25000							
	RADOME FAB 3 ea.			9000							
	CORRUGATION TOOL			25000							
	CORRUGATION FAB			10000							
	PCB		470								
	PCB FAB			17500							
	CONNECTOR		150								
	ROTARY JOINT			10000							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		40220	136500							32540

TOTAL $ 209260

TOTAL EA $ 2092

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT
28	9dB CORNER REFLECT	10000									
	FAB DETAIL PARTS				7146.46				36620.35	43766.81	1750656
	RADOME TOOL OUTER			25000							
	RADOME TOOL INNER			25000							
	RADOME TOOL INSIDE			25000							
	RADOME FAB 3 ea.			7500							
	CORRUGATION TOOL			35000							
	CORRUGATION FAB			750000							
	PCB		47000								
	PCB FAB			65000							
	CONNECTOR		15000								
	ROTARY JOINT			750000							
	MOTOR		400000								
	SERVO AMP		500000								
	BELT		7500								
	SHAFT		10000								
	BEARING LOWER		10000								
	UPPER		2500								
	BASE SUPPORT		20000								
	MTG HARDWARE		10000								
	ASSY & TEST									13250	530000
	TOTAL		1022000	1251500							2280656

TOTAL B 5560153

TOTAL EA 5562

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS	UNIT
29A	6.7.12dB PATCH ARRAY	100									
	FAB DETAIL PARTS				49.27		231.14		1379.33	1659.74	66390
	RADOME TOOLING			25000							
	RADOME FABRICATION			2500							
	PCB MATERIAL		470								
	PCB FAB			7500							
	CONNECTORS		300								
	CABLE		50								
	DIODE MODULATOR		250								
	ROTARY JOINT			10000							
	MOTOR		12700								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	BASE SUPPORT		1000								
	MTG HARDWARE		1000								
	ASSY & TEST										
										280	11200
	TOTAL		38170	46000							77590

TOTAL $161760

TOTAL EA $1618

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE_____ OF_____

PROPOSAL_____ PREPARED_____ DATE_____

PROPOSAL ITEM_____ MQ. NO._____ APPROVED_____ DATE_____

QUOTE NO._____ APPROVED_____ DATE_____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL HOURS (UNIT)	UNIT AVERAGE HOURS
29B	6.9.12dB PATCH ARRAY	10000									
	FAB DETAIL PARTS				3816.35		18889.33		113651.33	136357.0	545428.0
	RADOME TOOLING			25000							
	RADOME FABRICATION			300000							
	PCB MATERIAL		47000								
	PCB FAB			650000							
	CONNECTORS		30000								
	CABLE		5000								
	DIODE MODULATOR		20000								
	ROTARY JOINT			750000							
	MOTOR		400000								
	SERVO AMP		500000								
	BELT		7500								
	SHAFT		10000								
	BEARING LOWER		10000								
	UPPER		2500								
	BASE SUPPORT		20000								
	MTG HARDWARE		10000								
	ASS & TEST									13250	530000
	TOTAL		1062000	1725000							5984280

TOTAL $ 7712800

TOTAL EA 877

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-24/SCC-24 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT
30	6dB CONFORMAL ARRAY	100									
	FAB DETAIL PARTS				1386		1713		42548	71592	28637
	RADOME/COVER		3250								
	PCB MATERIAL		10750								
	PHASE SHIFTER		160000								
	MICROPROCESSOR		20000								
	CONNECTOR RF		150								
	CONNECTOR & CABLE		10000								
	TOTAL		204150								28637

TOTAL 232787

TOTAL EA 2328

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT
31	8dB CONFORMAL ARRAY	10000									
	FAB DETAIL PARTS				9810.72		14176.28		3507.13	59054.3	236233
	RADOME/COVER		3250000								
	PCB MATERIAL		1075000								
	PHASE SHIFTER		1280000								
	MICROPROCESSOR		1800000								
	CONNECTOR RF		15000								
	CONNECTOR CABLE		9000								
	TOTAL		16024000								236233

TOTAL $ 18386332

TOTAL EH 1839

CF 11-16-86

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT $
32	9dB CONFORMAL ARRAY	100									
	FAB DETAIL PARTS				208 00		299.91		744.95	1252.86	5014
	RADOME/COVER		6500								
	RF MATERIAL		19500								
	PHASE SHIFTER		260000								
	MICROPROCESSOR		20000								
	CONNECTOR RF		150								
	CONNECTOR CABLE		12000								
	TOTAL		318150								5014

TOTAL $ 368264

TOTAL EA $ 3683

CF 11-1E-4G

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ HQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT
33	9dB CONFORMAL ARRAY										
	FAB DETAIL PARTS				1916876		2180849		637476	103952.01	4134.080
	RADOME/COVER		650000								
	PCB MATERIAL		185000								
	PHASE SHIFTER		2085000								
	MICROPROCESSOR		180000								
	CONNECTOR RF		15000								
	CONNECTOR & CABLE		9006								
	TOTAL		2453900								4134.080

TOTAL 28673080
TOTAL EA 6867

CF 11-16-4G

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT $
34	6dB RING ARRAY	100									
	DETAIL PARTS FAB			15000	321.9	413.5	286.79		426.77	1129	45080
	UPPER PLATE TOOL			1500							
	UPPER PLATE CAST			1500							
	LOWER PLATE TOOL			1500							
	LOWER PLATE CAST			1800							
	REED SWITCH		11500								
	MAGNETS		3900								
	ARRAY PCB		200								
	FEED PCB MAT		7300								
	ROTARY JOINT		10000								
	MOTOR		5000								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		61300	21600							56280

TOTAL A 139 180

TOTAL EA #1392

CF 11-16-46

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT $
35	60 PRINT ARRAY	10000									
	DETAIL PARTS FAB			15000	2620.39	765.03	2359.65		3513.07	92496	36.9840
	UPPER PLATE TOOL			1500							
	UPPER PLATE COST			150000							
	LOWER PLATE TOOL			1500							
	LOWER PLATE COST			15000							
	REED SWITCH		100000								
	MAGNETS		35000								
	ARRAY PCB		20000								
	FEED PBC MAT		730000								
	ROTARY JOINT		750000								
	MOTOR		500000								
	SERVO AMP		2000000								
	BELT		7500								
	SHAFT		10000								
	BEARING LOWER		10000								
	UPPER		2500								
	MTG HARDWARE		10000								
	ASSY & TEST									1325D	530000
	TOTAL		4175000	318000							4229840

CP 11-16-66

TOTAL $ 8719840

TOTAL EA $ 872

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CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE ___ OF ___

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ MQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT $
36	96BRING ARRAY	100									
	DETAIL PARTS FAB			15000	641.80	185.06	560.07		858.53	2253.9	90159
	UPPER PLATE TOOL			1500							
	UPPER PLATE COST			1800							
	LOWER PLATE TOOL			1500							
	LOWER PLATE COST			1800							
	REED SWITCH		23000								
	MAGNETS		4800								
	ARRAY PCB		400								
	FEED PRC MAT		14600								
	ROTARY JOINT		10000								
	MOTOR		5000								
	SERVO AMP		20000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		800								
	UPPER		500								
	MTG HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		81200	21600							101359

TOTAL 204159

TOTAL EA 2042

CF 11-16-86

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ HQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-27/SCC-27 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-77/SCC-77 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT $
37	9 BRING ARRAY	10000									
	DETAIL PARTS FAB			15000	5240.27	15130.03	4719.67		7026.53	184991.44	7.39965 7
	UPPER PLATE TOOL			1500							
	UPPER PLATE COST			150000							
	LOWER PLATE TOOL			1500							
	LOWER PLATE COST			150000							
	REED SWITCH		200000								
	MAGNETS		75000								
	ARRAY PCB		40000								
	FEED PBC MAT		1460000								
	ROTARY JOINT		750000								
	MOTOR		500000								
	SERVO AMP		2000000								
	BELT		7500								
	SHAFT		10000								
	BEARING LOWER		10000								
	UPPER		2500								
	MTG HARDWARE		10000								
	ASSY & TEST									13250	530000
	TOTAL		5065000	318000							7929657

TOTAL $ 13312657

TOTAL EA 1331

CF 11-16-4G

CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____

PROPOSAL ITEM _____ MQ. NO. _____ PREPARED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-24/SCC-24 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT
36	12dBRING ARRAY	100									
	DETAIL PARTS FAB			15000	895.74	246.74	76.76		138.05	3005.29	12012
	UPPER PLATE TOOL			1500							
	UPPER PLATE COST			1800							
	LOWER PLATE TOOL			1500							
	LOWER PLATE COST			1800							
	REED SWITCH		30100								
	MAGNETS		10400								
	ARRAY PCB		540								
	FEED PCB MAT		19500								
	ROTARY JOINT		10000								
	MOTOR		5000								
	SERVO AMP		2000								
	BELT		100								
	SHAFT		1000								
	BEARING LOWER		900								
	UPPER		500								
	MTG. HARDWARE		1000								
	ASSY & TEST									280	11200
	TOTAL		144450	21600							131412

TOTAL $297462

TOTAL EA $2946

CF 11-16-4

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CUBIC CORPORATION

COST PROPOSAL ESTIMATE
MANUFACTURING LABOR, MATERIAL AND TOOLING SUMMARY

PAGE _____ OF _____

PROPOSAL _____ PREPARED _____ DATE _____

PROPOSAL ITEM _____ HQ. NO. _____ APPROVED _____ DATE _____

QUOTE NO. _____ APPROVED _____ DATE _____

ITEM	PART NUMBER OR DESCRIPTION	QTY.	MATERIAL $	SUBCONTRACT $	MANUFACTURING HOURS CC-22/SCC-22 LCU	CC-25/SCC-25 LCU	CC-26/SCC-26 LCU	CC-27/SCC-27 LCU	CC-28/SCC-28 LCU	TOTAL	UNIT $
39	2dBRING ARRAY	10000									
	DETAIL PARTS FAB			15.000	69810.39	20123.4		62929.13	93690.08	246655.25	9861.310
	UPPER PLATE TOOL			1.500							
	UPPER PLATE COST			150.000							
	LOWER PLATE TOOL			1500							
	LOWER PLATE COST			150.000							
	REED SWITCH		2689000								
	MAGNETS		100000								
	ARRAY PCB		54000								
	FEED PRC MAT		1950000								
	ROTARY JOINT		750000								
	MOTOR		500.000								
	SERVO AMP		2000000								
	BELT		7400								
	SHAFT		10000								
	BEARING LOWER		10000								
	UPPER		2500								
	MTG HARDWARE		10000								
	ASSY & TEST									1325.0	530000
	TOTAL		8063000	318000							10396210

TOTAL 1877210

TOTAL EA 1878

CF T1-16-4G

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